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AFAL-TR-75-92

VARIABLE CAPACITANCE ELECTROSTATIC ENERGY CONVERSION SYSTEM

APRIL 1976

TECHNICAL REPORT AFAL-TR-75-92

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Energy Conversion	Generator
System	Motor
Power	Mechanical
CW	Electrical

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Energy conversion is obtained by operation of variable capacitance electrostatic generators, involving contained charge, in paired opposition to one another across the load (or electrical source of power), either directly or indirectly through dielectric material, to provide for conversion of mechanical energy to electrical energy (or electrical energy to mechanical energy).

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FOREWORD

This report was prepared by the Electro-Optics Technology Branch, Electronic Technology Division, Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio under Task 200101, "Gaseous Lasers", of Project 2001, "Laser Technology".

The technical information in this report was originally contained in unpublished technical papers describing an invention by the author for energy conversion by use of variable capacitance electrostatic generators.

This report was submitted by the author on 23 April 1975.

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SECTION I
INTRODUCTION

Energy conversion is obtained for the Variable Capacitance Electrostatic Energy Conversion System by operation of variable capacitance electrostatic generators, involving contained charge, in paired opposition to one another across the load(or electrical source of power),either directly or indirectly through dielectric material, to provide for conversion of mechanical energy to electrical energy(or electrical energy to mechanical energy).

For a variable capacitance electrostatic generator (Reference 1), the electrical power input to the capacitor, P_e (watts), is equal to the increase in capacitor electrostatic field energy, W_{ef} (joules), per unit time, t (seconds), and the mechanical power output, P_M (watts):

$$P_e = \frac{dW_{ef}}{dt} + P_M \tag{1}$$

with

$$P_e = \frac{Vdq}{dt} \tag{2}$$

V = capacitor potential (volts)

q = charge on capacitor (coulombs)

and

$$W_{ef} = \frac{1}{2} CV^2 \tag{3}$$

C = capacitor capacitance (farads)

Also,

$$q = CV \tag{4}$$

Therefore,

$$P_M = \frac{1}{2} V^2 \frac{dC}{dt} \tag{5}$$

and the time rate of conversion of mechanical to electrical energy, dW_{ME}/dt, equal to $-P_M$, is given as

$$\frac{dW_{ME}}{dt} = -\frac{1}{2} V^2 \frac{dC}{dt} \tag{6}$$

Conversion of mechanical shaftpower to electrical power to a load by variable capacitance electrostatic generators operating in paired opposition to one another across the load (and involving contained charge) shall be considered first.

As an example, a specific physical arrangement of the electrostatic generators operating in paired opposition to one another connected directly to the load R (ohms) is presented in Figure 1A; a schematic for the arrangement is presented in Figure 1B.

The capacitors each range in value from high capacitance C_H to low capacitance C_L and are coupled by the drive shaft so that they operate in opposition to each other; that is, when one capacitor has value C_H, the other capacitor has value C_L, and vice versa. The capacitors each essentially possess a charge Q, and hence there exists a contained

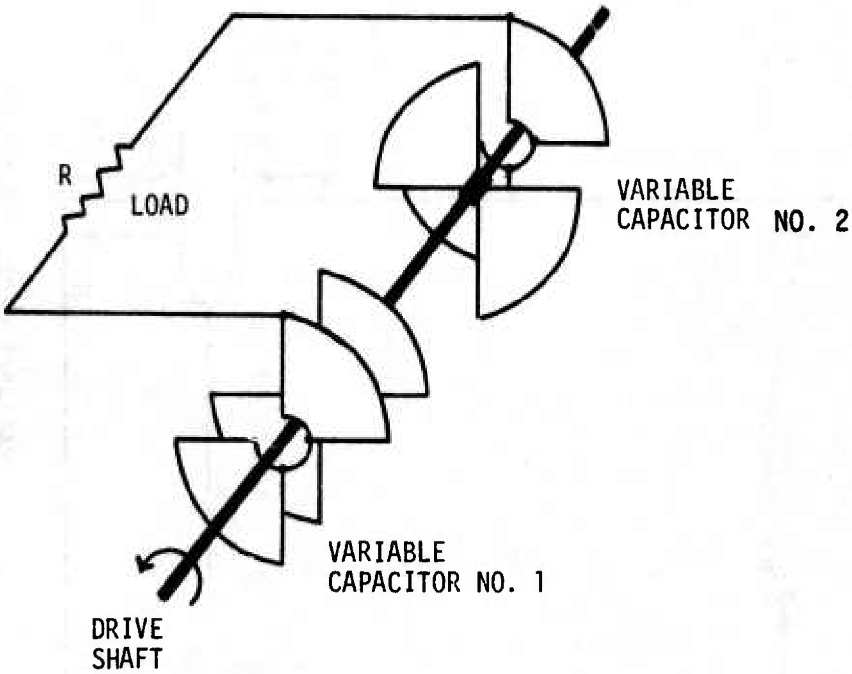
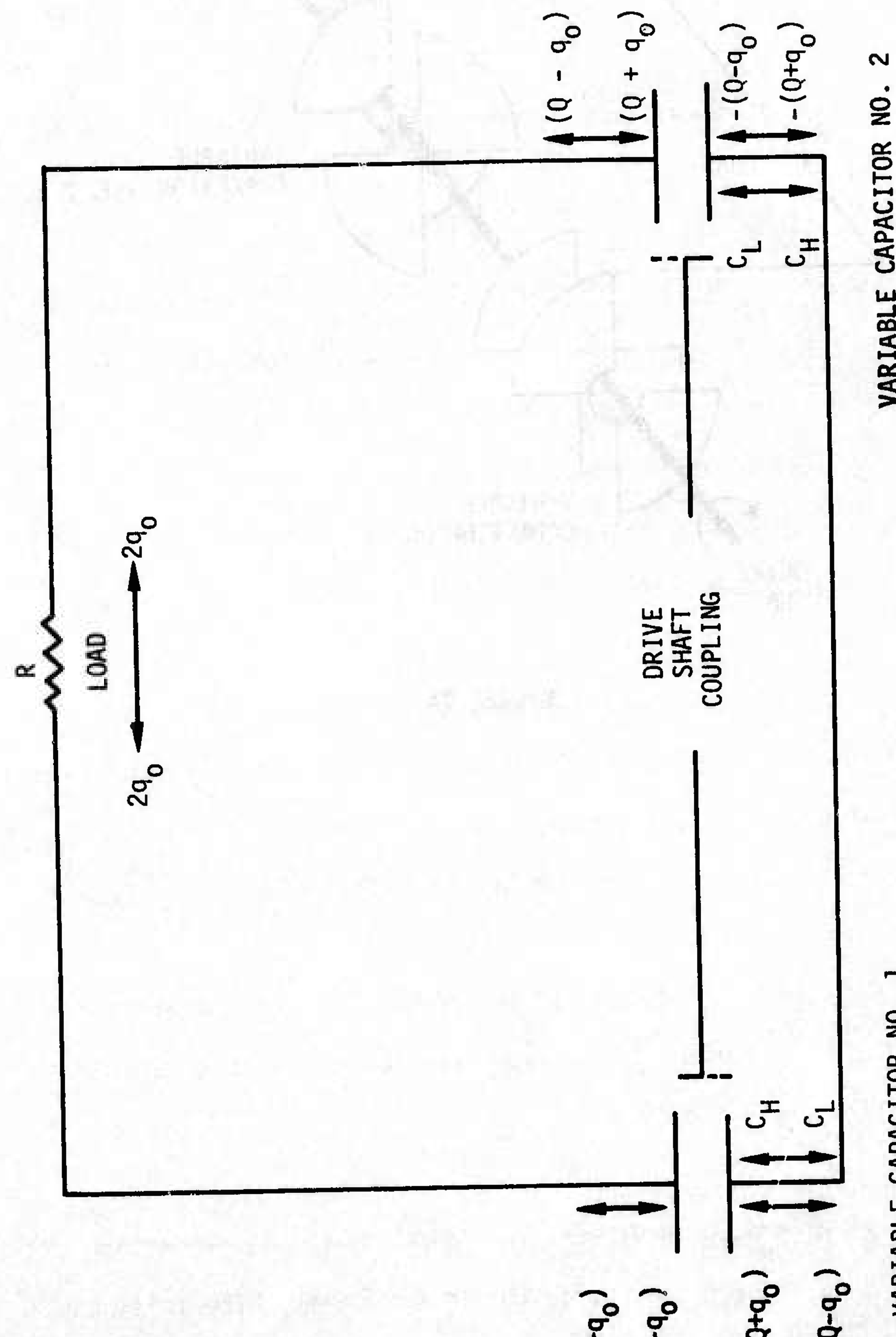

R
LOAD
VARIABLE
CAPACITOR NO. 2
VARIABLE
CAPACITOR NO. 1
DRIVE
SHAFT

Figure 1A



(Q - q_o)
(Q + q_o)
-(Q-q_o)
-(Q+q_o)
C_L
C_H
VARIABLE CAPACITOR NO. 2
R
LOAD
2q_o
2q_o
DRIVE SHAFT COUPLING
(Q+q_o)
(Q-q_o)
-(Q+q_o)
-(Q-q_o)
C_H
C_L
VARIABLE CAPACITOR NO. 1

Figure 1B

(or "trapped") charge of 2Q for the system. As Variable Capacitor #1 varies from C_H to C_L, its charge varies from $(Q + q_0)$ to $(Q - q_0)$; as Variable Capacitor #2 varies from C_L to C_H, its charge varies from $(Q - q_0)$ to $(Q + q_0)$. A charge $2q_0$ is directly transferred across the load R; mechanical energy is converted to electrical energy by Variable Capacitor #1 and electrical energy is converted to mechanical energy by Variable Capacitor #2. However, since Capacitor #2 is drive-shaft coupled to Capacitor #1, this mechanical energy may be considered as simultaneously reconverted to electrical energy. Capacitor #1 is now in the state initially occupied by Capacitor #2; Capacitor #2 is now in the state initially occupied by Capacitor #1. As the drive shaft continues to rotate, the capacitors return to their respective initial states with another transfer of charge $2q_0$ across the load, and a cycle is completed.

A physical arrangement of the electrostatic generators operating in paired opposition to one another, indirectly connected to the load through dielectric insulating material, is presented in Figure 1C; a schematic for the arrangement is presented in Figure 1D.

For one cycle, a charge $4q_0$ is transferred by displacement across the load; there is charge q_0 associated with the dielectric material capacitors of capacitance c_d.

The cases presented above were for initial explicit exposition of the concept involved for the Energy Conversion System. The following cases, presented in more detail, are again essentially for exposition of the concept involved for the Energy Conversion System and should not be considered as limiting its range of application.

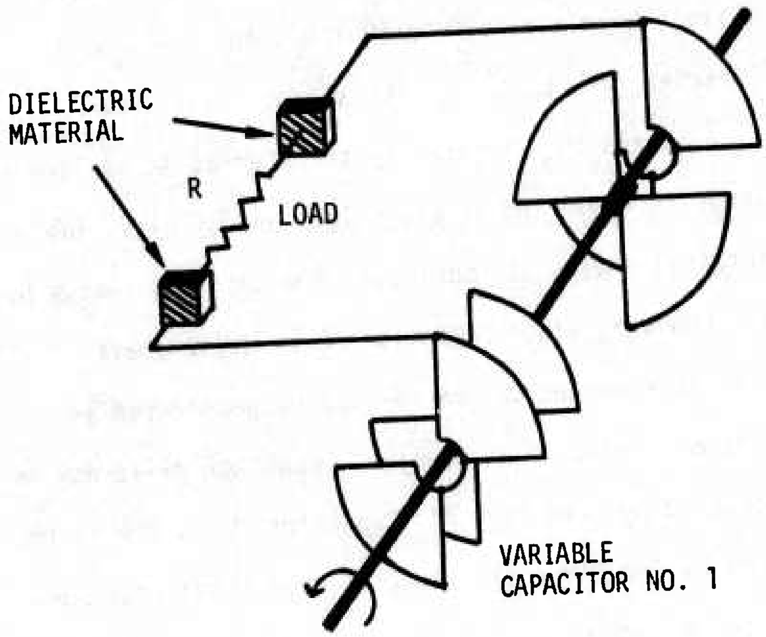

DIELECTRIC
MATERIAL
R
LOAD
VARIABLE
CAPACITOR NO. 2
VARIABLE
CAPACITOR NO. 1
DRIVE
SHAFT

Figure 1C

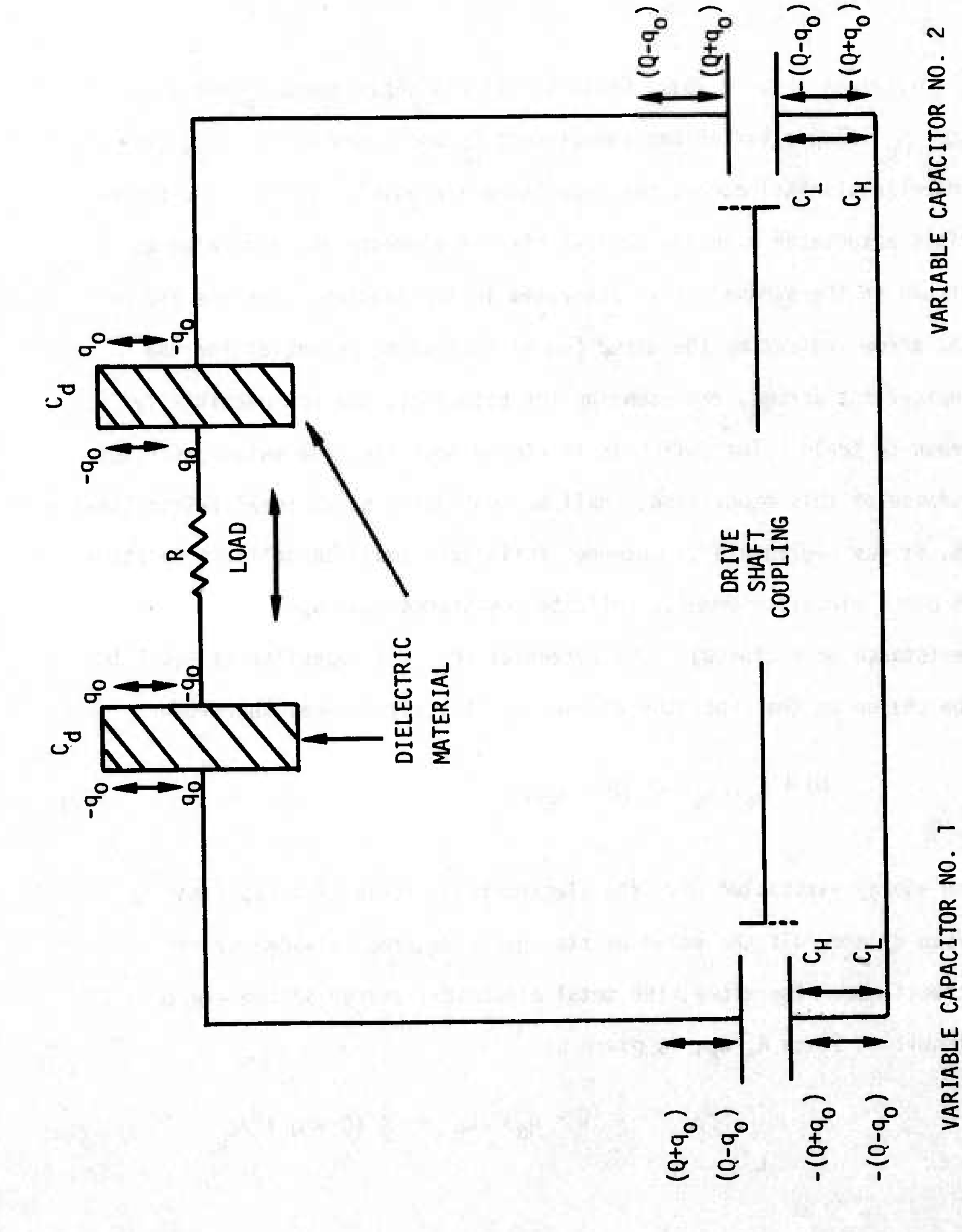

VARIABLE CAPACITOR NO. 1
VARIABLE CAPACITOR NO. 2
DRIVE SHAFT COUPLING
DIELECTRIC MATERIAL
LOAD
R
C_d
C_d
C_H
C_L
C_L
C_H
q_o
$-q_o$
$(Q+q_o)$
$(Q-q_o)$
$-(Q+q_o)$
$-(Q-q_o)$

Figure 1D

SECTION II

PULSED ENERGY INPUT, GENERATORS DIRECTLY CONNECTED TO LOAD

State A (Figure 2A): Capacitor #1 has capacitance C_H and a charge $(Q + q_o)$; Capacitor #2 has capacitance C_L and a charge $(Q - q_o)$; the potentials(volts) across the capacitors are equal. (NOTE: The potentials associated with the various circuit elements are indicated by arrows in the schematics as presented in the figures, with the tip of the arrow indicating the direction of increasing potential for the charge; the arrows, representing the potential, are not necessarily drawn to scale.) The switch is in closed position; the switch, for the purpose of this exposition, shall be considered as an ideal switch (that is, it has negligible inductance, infinitely small capacitance relative to other circuit elements, infinite resistance when open, and zero resistance when closed). The potential across a capacitor is equal to the charge on the capacitor divided by its capacitance, therefore:

$$(Q + q_o)/C_H = (Q - q_o)/C_L \tag{7}$$

The energy associated with the electrostatic field of a capacitor is given by one-half the value of its charge squared, divided by its capacitance. Therefore, the total electrical energy of the electric circuit in State A, W_A, is given as

$$W_A = \frac{1}{2}(Q + q_o)^2/C_H + \frac{1}{2}(Q - q_o)^2/C_L \tag{8}$$

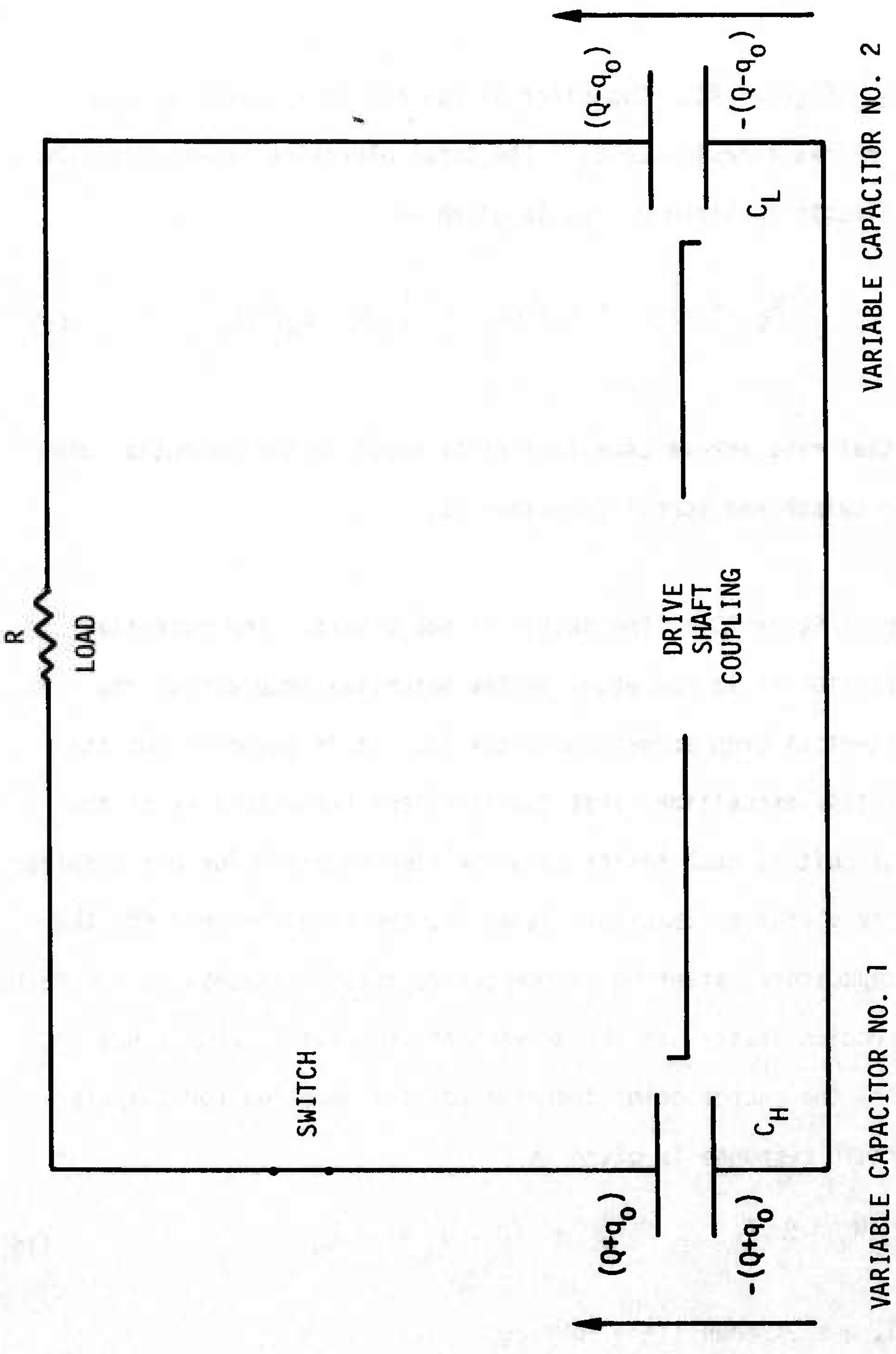

(Q-q$_o$)
-(Q-q$_o$)
C$_L$
VARIABLE CAPACITOR NO. 2
R
LOAD
DRIVE
SHAFT
COUPLING
SWITCH
C$_H$
(Q+q$_o$)
-(Q+q$_o$)
VARIABLE CAPACITOR NO. 1

Figure 2A

The switch is opened and, as the drive shaft rotates, the capacitances of Capacitors #1 and #2 change.

State B(Figure 2B): Capacitor #1 now has capacitance C_L and Capacitor #2 has capacitance C_H. The total electrical energy for the electric circuit in State B, W_B, is given as

$$W_B = \frac{1}{2}(Q + q_o)^2/C_L + \frac{1}{2}(Q - q_o)^2/C_H \qquad (9)$$

The potential rise across Capacitor #1 is equal to the potential drop across the switch and across Capacitor #2.

State C(Figure 2C): The switch is now closed. The potential rise across Capacitor #1 is now equal to the potential drop across the load and the potential drop across Capacitor #2. It is assumed, for the purpose of this exposition, that the transient response time of the electric circuit is much faster than the time required for one complete cycle of the variable capacitors (that is, the time required for the variable capacitors, starting at respective initial states, to return to those respective states, as the drive shaft rotates). With q now representing the charge being transferred, the equation for the electrical circuit response is given as

$$(Q + q_o - q)/C_L = R\frac{dq}{dt} + (Q - q_o + q)/C_H \qquad (10)$$

When $t = 0$, $q = 0$; when $t = \infty$, $q = 2q_o$.

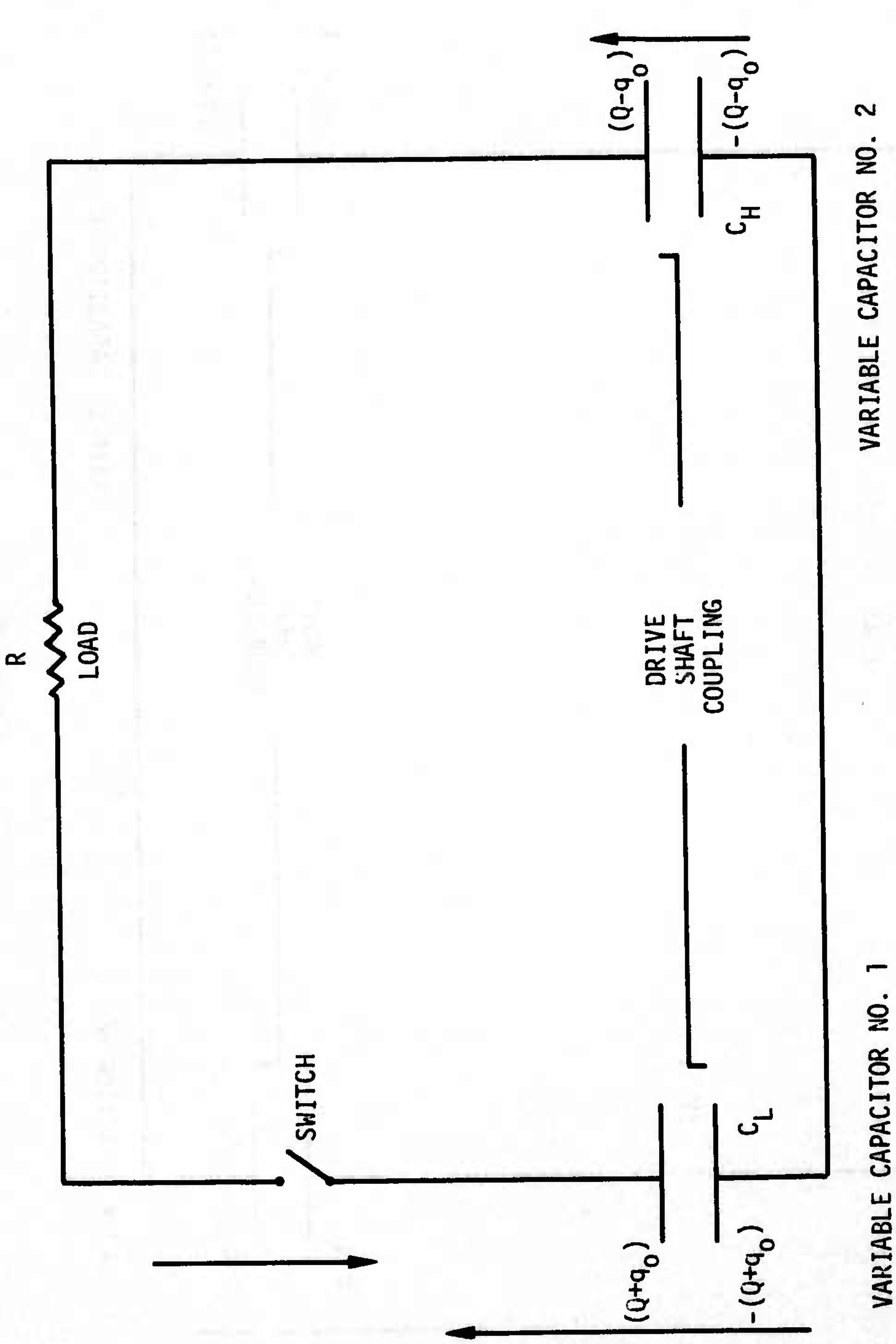

R
LOAD
SWITCH
DRIVE
SHAFT
COUPLING
(Q-q$_o$)
-(Q-q$_o$)
C$_H$
VARIABLE CAPACITOR NO. 2
(Q+q$_o$)
-(Q+q$_o$)
C$_L$
VARIABLE CAPACITOR NO. 1

Figure 2B

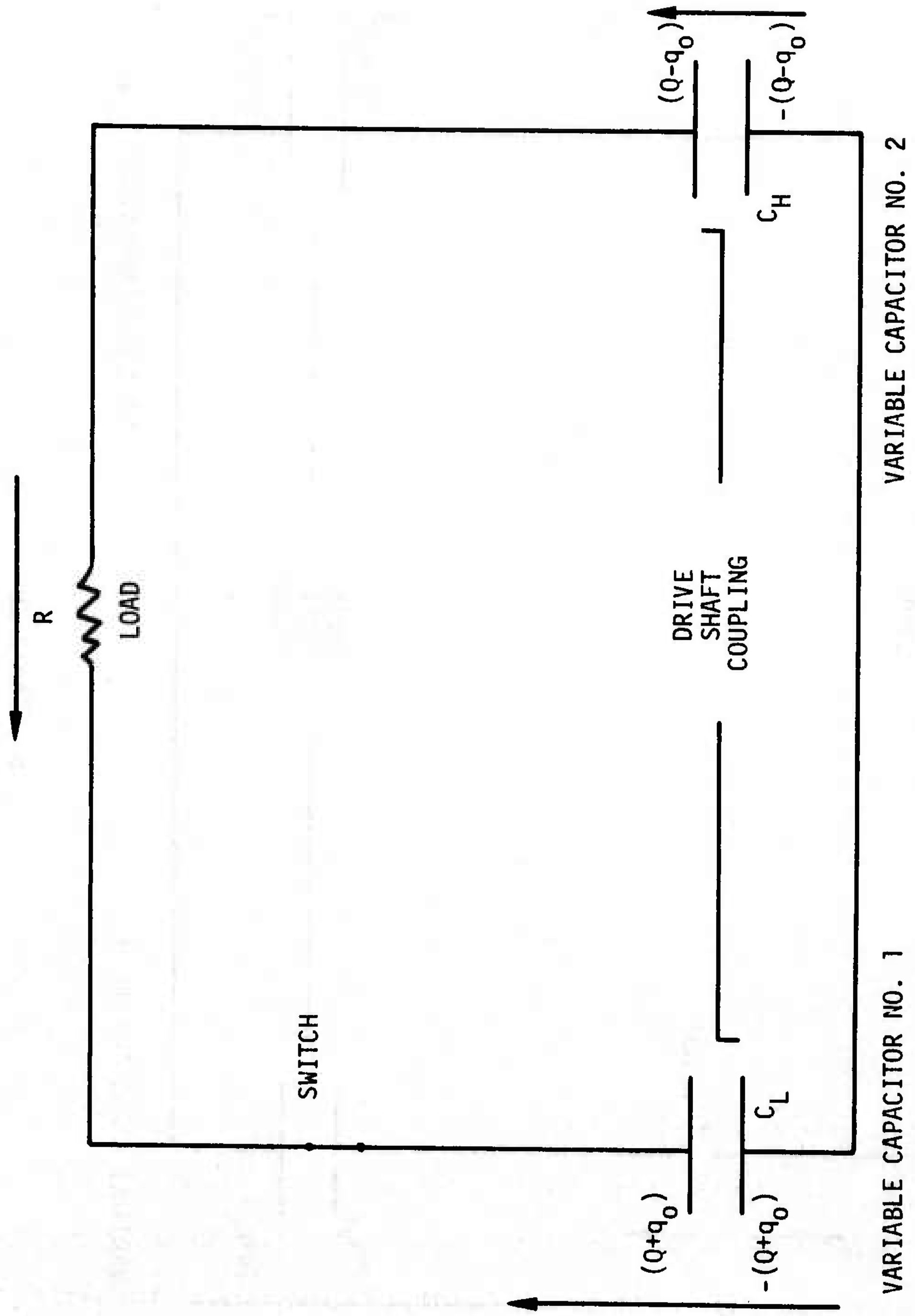

R
LOAD
$(Q-q_o)$
$-(Q-q_o)$
C_H
VARIABLE CAPACITOR NO. 2
DRIVE
SHAFT
COUPLING
SWITCH
C_L
$(Q+q_o)$
$-(Q+q_o)$
VARIABLE CAPACITOR NO. 1

Figure 2C

The solution of Equation (10) is given as follows:

$$q = 2q_o \left[1 - \exp\left[-\frac{1}{R}\,(1/C_L + 1/C_H)t \right] \right] \quad (11)$$

With, as given by Equation (7),

$$q_o = \frac{(1/C_L - 1/C_H)}{(1/C_L + 1/C_H)}\, Q \quad (12)$$

<u>State D</u>(Figure 2D): After charge rearrangement, Capacitor #2 is in the same state as Capacitor #1 in State A; Capacitor #1 is in the same state as Capacitor #2 in State A; and the total electrical energy for the electrical circuit in State D, W_D, is given as

$$W_D = \frac{1}{2}\,(Q + q_o)^2/C_H + \frac{1}{2}\,(Q - q_o)^2/C_L \quad (13)$$

By use of Equations (9) and (13) it is seen that:

$$W_B - W_D = 2q_o^2(1/C_L + 1/C_H) = 4\left[\frac{1}{2}\,q_o^2(1/C_L + 1/C_H)\right] \quad (14)$$

$$\int_0^\infty R\left(\frac{dq}{dt}\right)^2 dt = 2q_o^2(1/C_L + 1/C_H) = W_B - W_D \quad (15)$$

Electrostatic energy is delivered to the load. As the drive shaft rotates, Capacitors #1 and #2 will again go through States B and C, with their roles interchanged, until the capacitors return to their respective states as given in State A. For this second half of the cycle, the same amount of energy is delivered to the load as was delivered in the

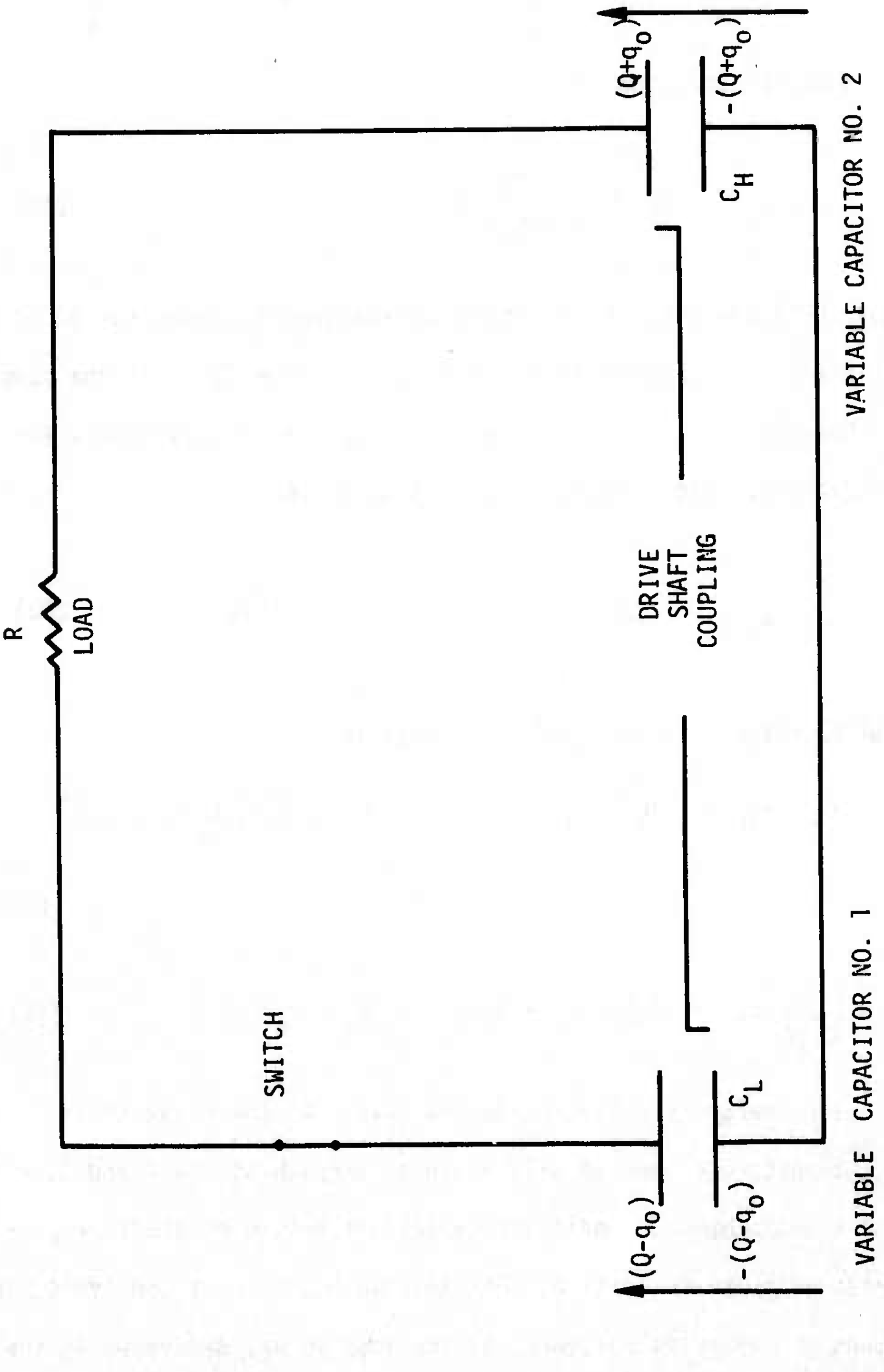

R
LOAD
SWITCH
DRIVE SHAFT COUPLING
$(Q+q_o)$
$-(Q+q_o)$
C_H
VARIABLE CAPACITOR NO. 2
$(Q-q_o)$
$-(Q-q_o)$
C_L
VARIABLE CAPACITOR NO. 1

Figure 2D

first half of the cycle; hence, the energy delivered to the load per cycle, W, is given as follows:

$$W = 2(W_B - W_D) = 8\left[\frac{1}{2} q_o^2 (1/C_L + 1/C_H)\right] \tag{16}$$

The limit on energy transfer may be determined as follows. The breakdown potential (References 1 and 2) for the variable capacitors, V_{CB} (volts), may be related to the charge on the variable capacitors:

$$(Q + q_o)/C_L = V_{CB} \tag{17}$$

By use of Equations (12) and (17) the limiting value of q_o may be given as follows:

$$q_o = (C_L/2)\,(1 - C_L/C_H)V_{CB} \tag{18}$$

By substitution of the above value of q_o into Equation (16), the limit on W, W_{CB}, is given as

$$W_{CB} = (1 + C_L/C_H)\,(1 - C_L/C_H)^2 C_L V_{CB}^2 \tag{19}$$

The range of W is then given as follows:

$$0 \leq W < W_{CB} \tag{20}$$

For non-negligible circuit inductance, such as, for example, a series inductance L(henries), the equation for the electrical circuit response is given as

$$(Q + q_o - q)/C_L = R\frac{dq}{dt} + L\frac{d^2q}{dt^2} + (Q - q_o + q)/C_H \qquad (21)$$

When $t = 0$, $q = 0$; when $t = \infty$, $q = 2q_o$; the solutions are given as follows:

For overdamped response, $(R/2L)^2 > (1/L)(1/C_L + 1/C_H)$,

$$q = 2Q\left[\frac{C_H - C_L}{C_H + C_L}\right]\left[1 - \exp\left(-\frac{Rt}{2L}\right)\left[\frac{R}{2La}\sinh(at) + \cosh(at)\right]\right] \qquad (22)$$

With

$$a = \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{L}\left(\frac{1}{C_L} + \frac{1}{C_H}\right)} \qquad (23)$$

For critically damped response, $(R/2L)^2 = (1/L)(1/C_L + 1/C_H)$,

$$q = 2Q\left[\frac{C_H - C_L}{C_H + C_L}\right]\left[1 - \exp\left(-\frac{Rt}{2L}\right) - \frac{Rt}{2L}\exp\left(-\frac{Rt}{2L}\right)\right] \qquad (24)$$

For underdamped response, $(R/2L)^2 < (1/L)(1/C_L + 1/C_H)$,

$$q = 2Q\left[\frac{C_H - C_L}{C_H + C_L}\right]\left[1 - \exp\left(-\frac{Rt}{2L}\right)\left[\frac{R}{2Lb}\sin(bt) + \cos(bt)\right]\right] \qquad (25)$$

With b being given by a, as defined above, divided by the square root of minus one.

The relation between Q and q_o is as given by Equation (12).

SECTION III

PULSED ENERGY INPUT, GENERATORS INDIRECTLY CONNECTED TO LOAD THROUGH DIELECTRIC MATERIAL

State A(Figure 3A): Capacitor #1 has capacitance C_H and a charge $(Q + q_o)$; Capacitor #2 has capacitance C_L and a charge $(Q - q_o)$. The potential rise across Capacitor #2 is equal to the potential drops across each dielectric (of capacitance c_d) and Capacitor #1:

$$(Q - q_o)/C_L = 2q_o/c_d + (Q + q_o)/C_H \tag{26}$$

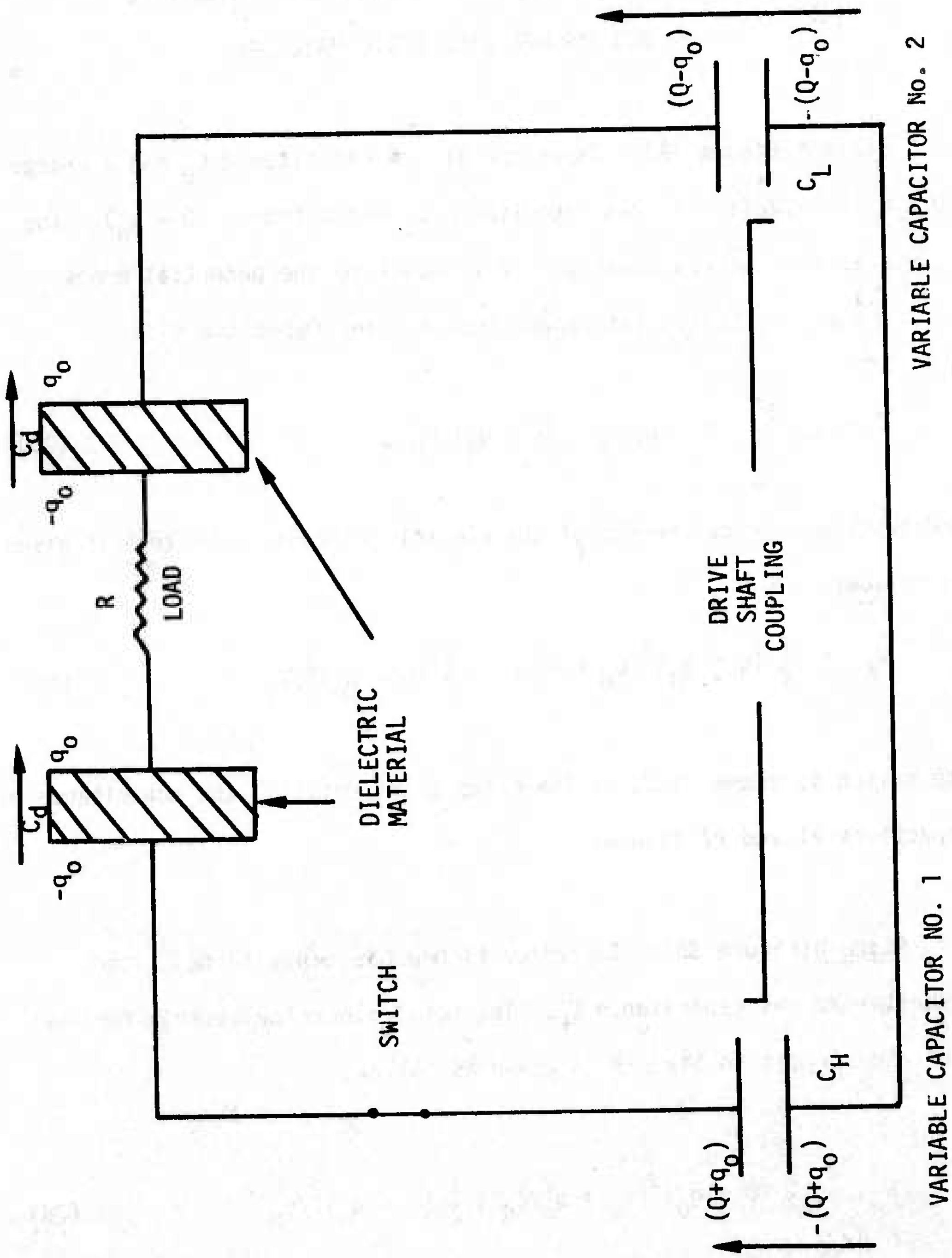
The total electrical energy of the electric circuit in State A is given as follows:

$$W_A = \frac{1}{2}(Q + q_o)^2/C_H + q_o^2/c_d + \frac{1}{2}(Q - q_o)^2/C_L \tag{27}$$

The switch is opened and, as the drive shaft rotates, the capacitance of Capacitors #1 and #2 changes.

State B(Figure 3B): Capacitor #1 now has capacitance C_L and Capacitor #2 has capacitance C_H. The total electrical energy for the electric circuit in State B is given as follows:

$$W_B = \frac{1}{2}(Q + q_o)^2/C_L + q_o^2/c_d + \frac{1}{2}(Q - q_o)^2/C_H \tag{28}$$



C_d
q_o
$-q_o$
C_d
q_o
$-q_o$
R
LOAD
DIELECTRIC MATERIAL
DRIVE SHAFT COUPLING
SWITCH
C_H
$(Q+q_o)$
$-(Q+q_o)$
C_L
$(Q-q_o)$
$-(Q-q_o)$
VARIABLE CAPACITOR NO. 1
VARIABLE CAPACITOR No. 2

Figure 3A

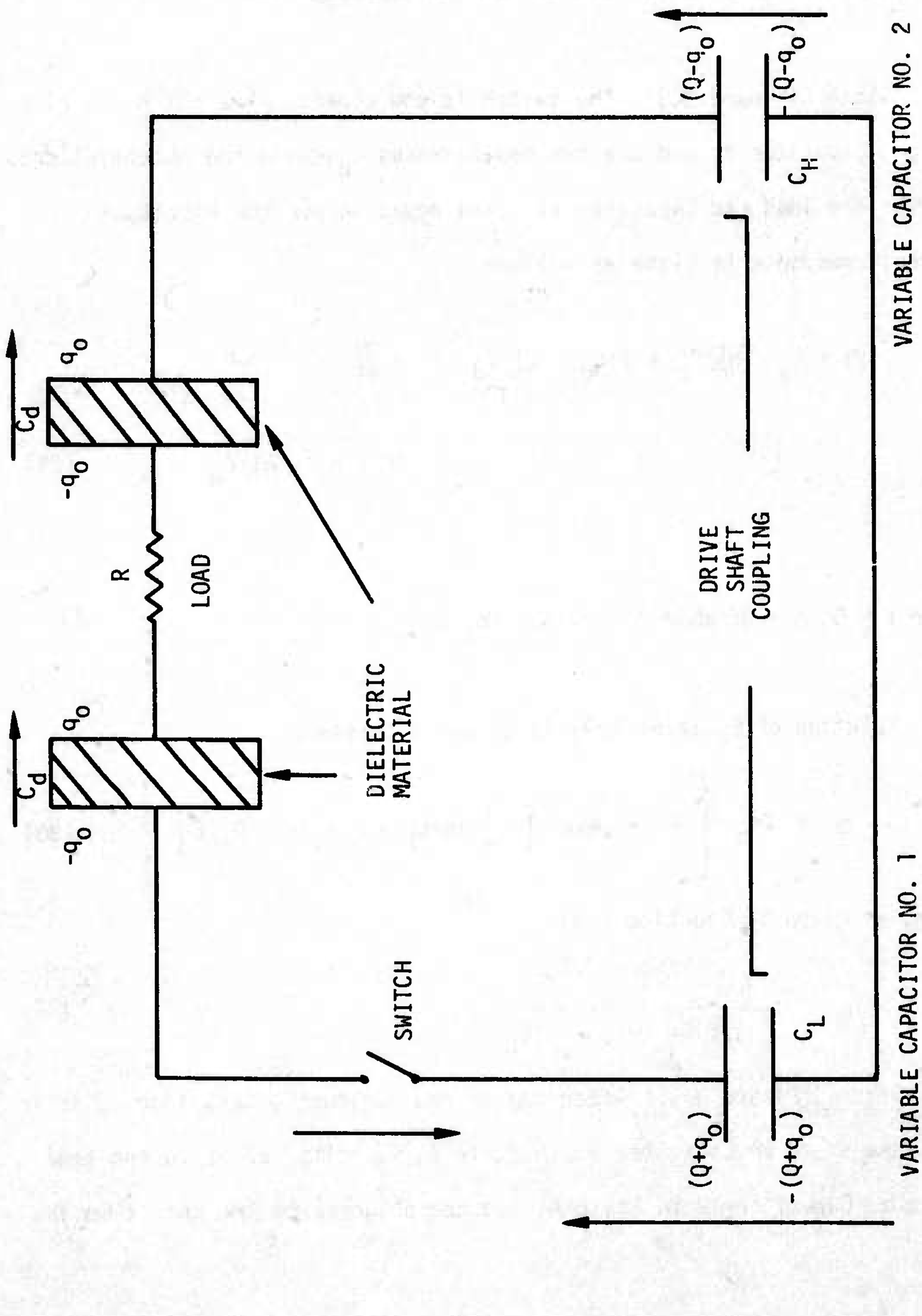

VARIABLE CAPACITOR NO. 2
$(Q-q_o)$
$-(Q-q_o)$
C_H
q_o
C_d
$-q_o$
R
LOAD
DRIVE
SHAFT
COUPLING
q_o
C_d
$-q_o$
DIELECTRIC
MATERIAL
SWITCH
C_L
$(Q+q_o)$
$-(Q+q_o)$
VARIABLE CAPACITOR NO. 1

Figure 3B

The potential rise across Capacitor #1 and the two capacitances c_d equals the potential drop across the switch and Capacitor #2.

State C(Figure 3C): The switch is now closed. The potential rise across Capacitor #1 and the two capacitances c_d equals the potential drop across the load and Capacitor #2. The equation for the electrical circuit response is given as follows:

$$(Q + q_o - q)/C_L + 2(q_o - q)/c_d = R\frac{dq}{dt} + (Q - q_o + q)/C_H \tag{29}$$

When $t = 0$, $q = 0$; when $t = \infty$, $q = 2q_o$.

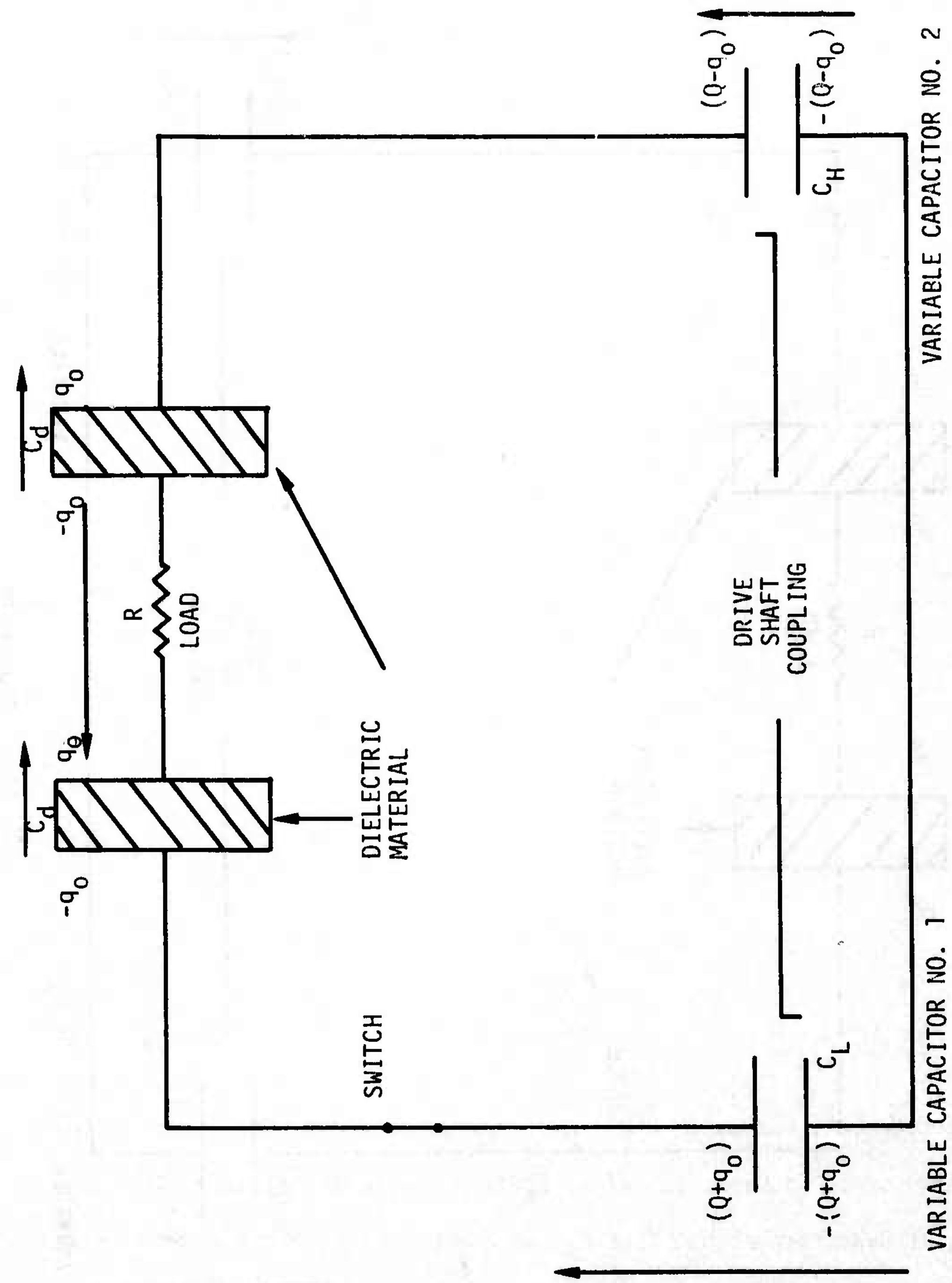
Solution of Equation (29) is given as follows:

$$q = 2q_o \left[1 - \exp\left[-\frac{1}{R}\left(1/C_L + 2/c_d + 1/C_H\right)t \right] \right] \tag{30}$$

With, as given by Equation (26),

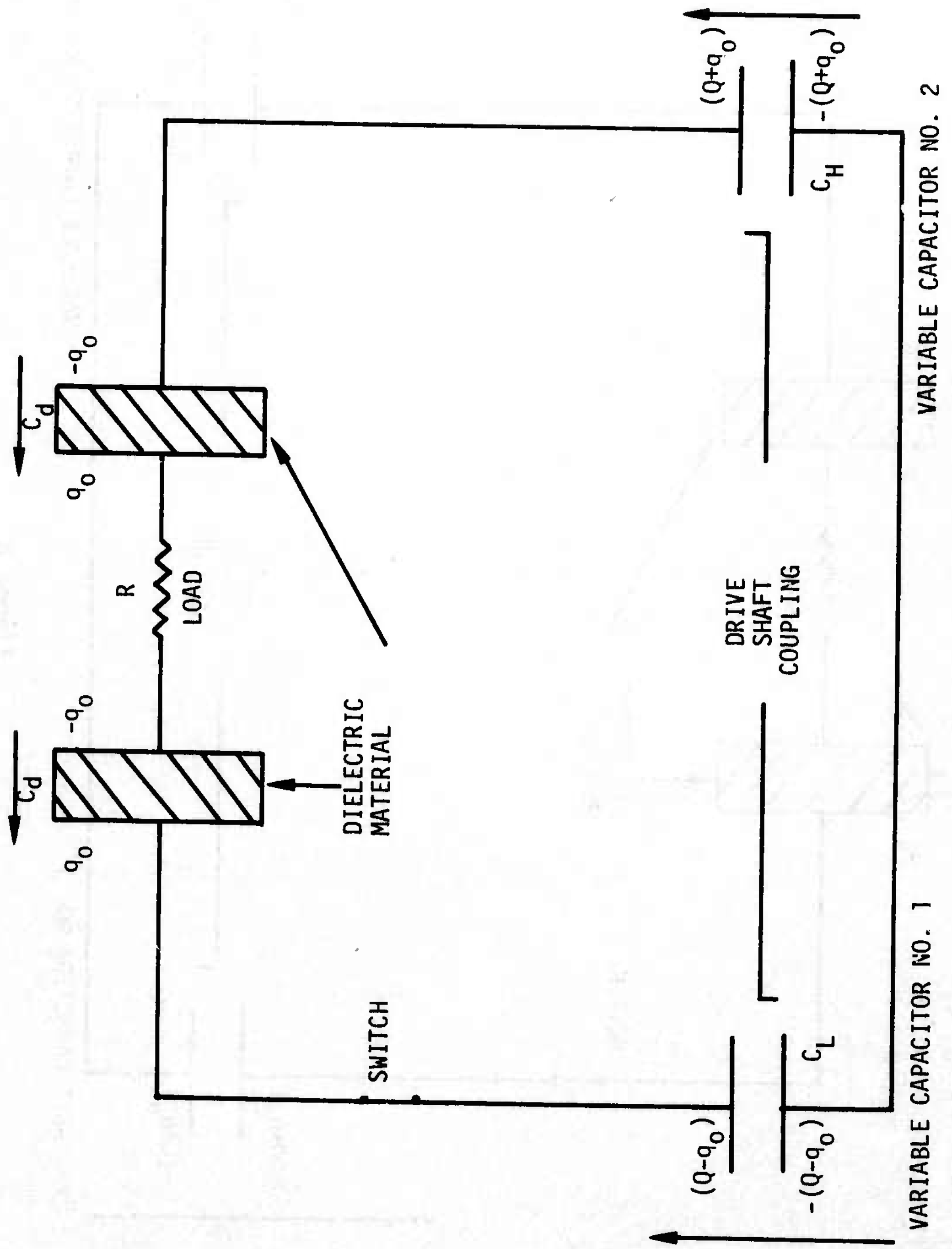
$$q_o = \frac{(1/C_L - 1/C_H)Q}{(1/C_L + 2/c_d + 1/C_H)} \tag{31}$$

State D(Figure 3D): After charge rearrangement, Capacitor #2 is in the same state as Capacitor #1 in State A; Capacitor #1 is in the same state as Capacitor #2 in State A; and the polarity of the charge on the



C_d
q_o
$-q_o$
C_d
q_o
$-q_o$
R
LOAD
DIELECTRIC MATERIAL
SWITCH
DRIVE SHAFT COUPLING
$(Q-q_o)$
$-(Q-q_o)$
C_H
C_L
$(Q+q_o)$
$-(Q+q_o)$
VARIABLE CAPACITOR NO. 2
VARIABLE CAPACITOR NO. 1

Figure 3C



q_o
C_d
$-q_o$
DIELECTRIC MATERIAL
R
LOAD
SWITCH
$(Q-q_o)$
$-(Q-q_o)$
C_L
VARIABLE CAPACITOR NO. 1
DRIVE SHAFT COUPLING
$(Q+q_o)$
$-(Q+q_o)$
C_H
VARIABLE CAPACITOR NO. 2

Figure 3D

dielectric capacitances has been reversed. The total electrical energy for the electric circuit in State D is given as follows:

$$W_D = \frac{1}{2}(Q + q_o)^2/C_H + q_o^2/c_d + \frac{1}{2}(Q - q_o)^2/C_L \tag{32}$$

By use of Equations (28), (32), and (31), it is seen that:

$$\begin{aligned} W_B - W_D &= 2q_o^2\,(1/C_L + 2/c_d + 1/C_H) \\ &= 4\left[\frac{1}{2}\,q_o^2\,(1/C_L + 2/c_d + 1/C_H)\right] \end{aligned} \tag{33}$$

By use of Equation (30), it is seen that:

$$\int_0^\infty R\left(\frac{dq}{dt}\right)^2 dt = 2q_o^2(1/C_L + 2/c_d + 1/C_H) = W_B - W_D \tag{34}$$

Electrostatic energy is delivered to the load. As the drive shaft rotates, Capacitors #1 and #2 will again go through States B and C, with their roles interchanged, until the capacitors return to their respective states as given in State A. For this second half of the cycle, the same amount of energy is delivered to the load as was delivered in the first half of the cycle; hence, the energy delivered to the load per cycle, W, is given as follows:

$$W = 2(W_B - W_D) = 8\left[\frac{1}{2}\,q_o^2\right](1/C_L + 2/c_d + 1/C_H) \tag{35}$$

Assuming q_o limited by the breakdown potential of the dielectric material (Reference 2), V_{dB},

$$q_o = c_d V_{dB} \tag{36}$$

Then, by use of Equations (35) and (36), the limit on W, W_{dB}, is given as follows:

$$W_{dB} = 4(c_d/C_L + 2 + c_d/C_H)c_d V_{dB}^2 \tag{37}$$

The range of W is then given as follows:

$$0 \leq W < W_{dB} \tag{38}$$

Reconsider Equation (29) such that R is a function of time, R = R{t}; for Q given in terms of q_o by Equation (31); and for q = 0 when t = 0; then the solution of Equation (29) is given as follows:

$$q = 2q_o \left[1 - \exp \left[- \int_0^t \frac{1}{R} (1/C_L + 2/c_d + 1/C_H) dt \right] \right] \tag{39}$$

With

$$\int_0^\infty R \left(\frac{dq}{dt} \right)^2 dt = 2q_o^2 (1/C_L + 2/c_d + 1/C_H) \tag{40}$$

SECTION IV

PULSED ENERGY INPUT, GENERATORS DIRECTLY CONNECTED TO LOAD, SELF-SWITCHING LOAD

<u>State A</u>(Figure 4A): Capacitor #1 has capacitance C_H and a charge $(Q + q_o)$; Capacitor #2 has capacitance C_L and a charge $(Q - q_o)$. The potential rise across Capacitor #2 is equal to the potential drop across Capacitor #1:

$$(Q - q_o)/C_L = (Q + q_o)/C_H \tag{41}$$

The load R is open to the electric circuit and the capacitance of the load area has the value C. The total electrical energy of the electric circuit in State A is given as follows:

$$W_A = \frac{1}{2}(Q + q_o)^2/C_H + \frac{1}{2}(Q - q_o)^2/C_L \tag{42}$$

The drive shaft rotates, the capacitance of Capacitors #1 and #2 changes, and the charge redistributes itself.

<u>State B</u>(Figure 4B): The instant of firing has been reached. A charge q_F has distributed itself with the capacitance across the load such that firing potential (or breakdown potential, Reference 2) V_F has been achieved across the load; V_F is equivalent to the product of the critical (firing) field E_F (volts/meter) and the distance across the load d (meters). Capacitor #1 now has capacitance C_L and Capacitor #2

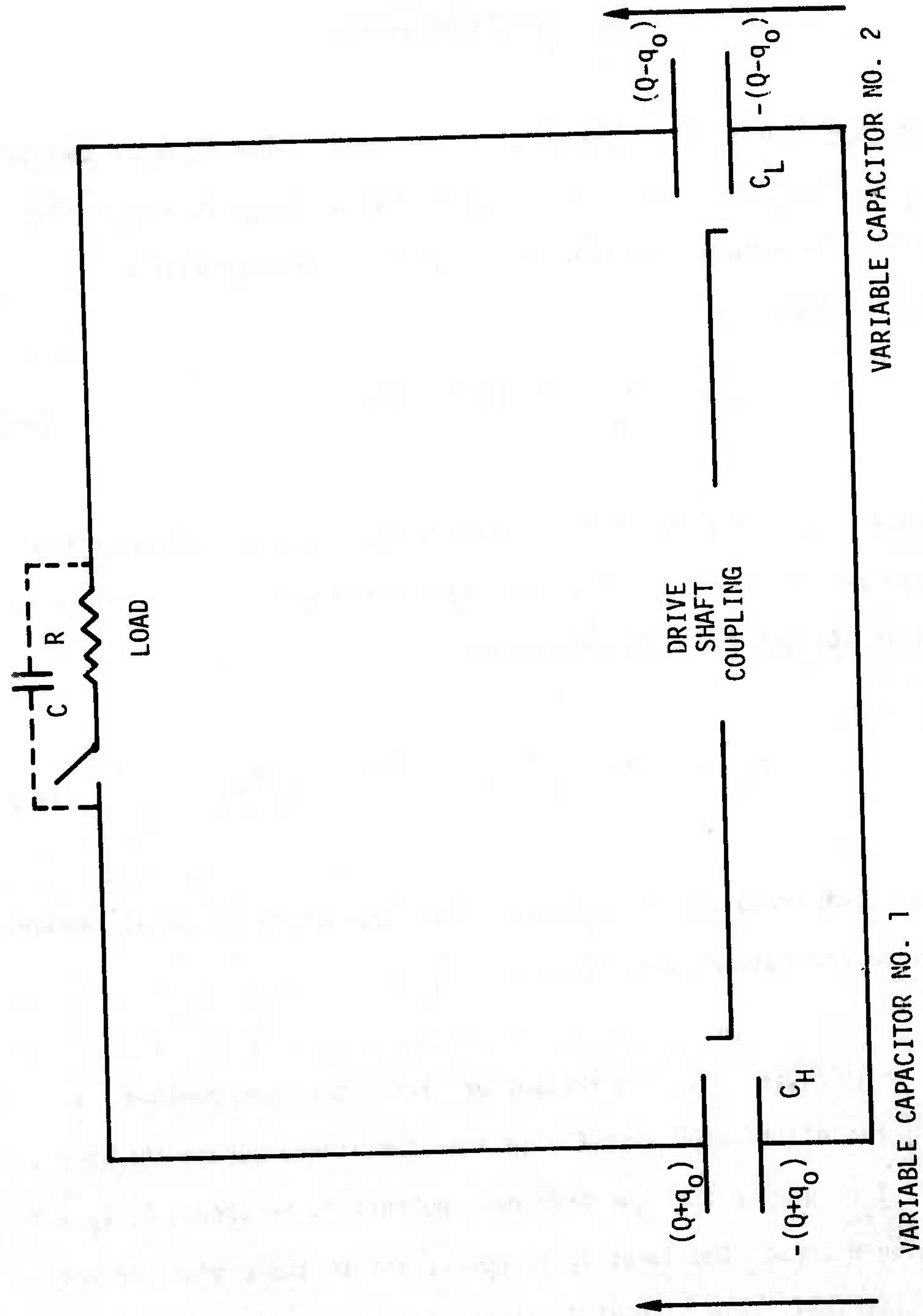

$(Q-q_o)$
$-(Q-q_o)$
C_L
VARIABLE CAPACITOR NO. 2
C
R
LOAD
DRIVE SHAFT COUPLING
C_H
$(Q+q_o)$
$-(Q+q_o)$
VARIABLE CAPACITOR NO. 1

Figure 4A

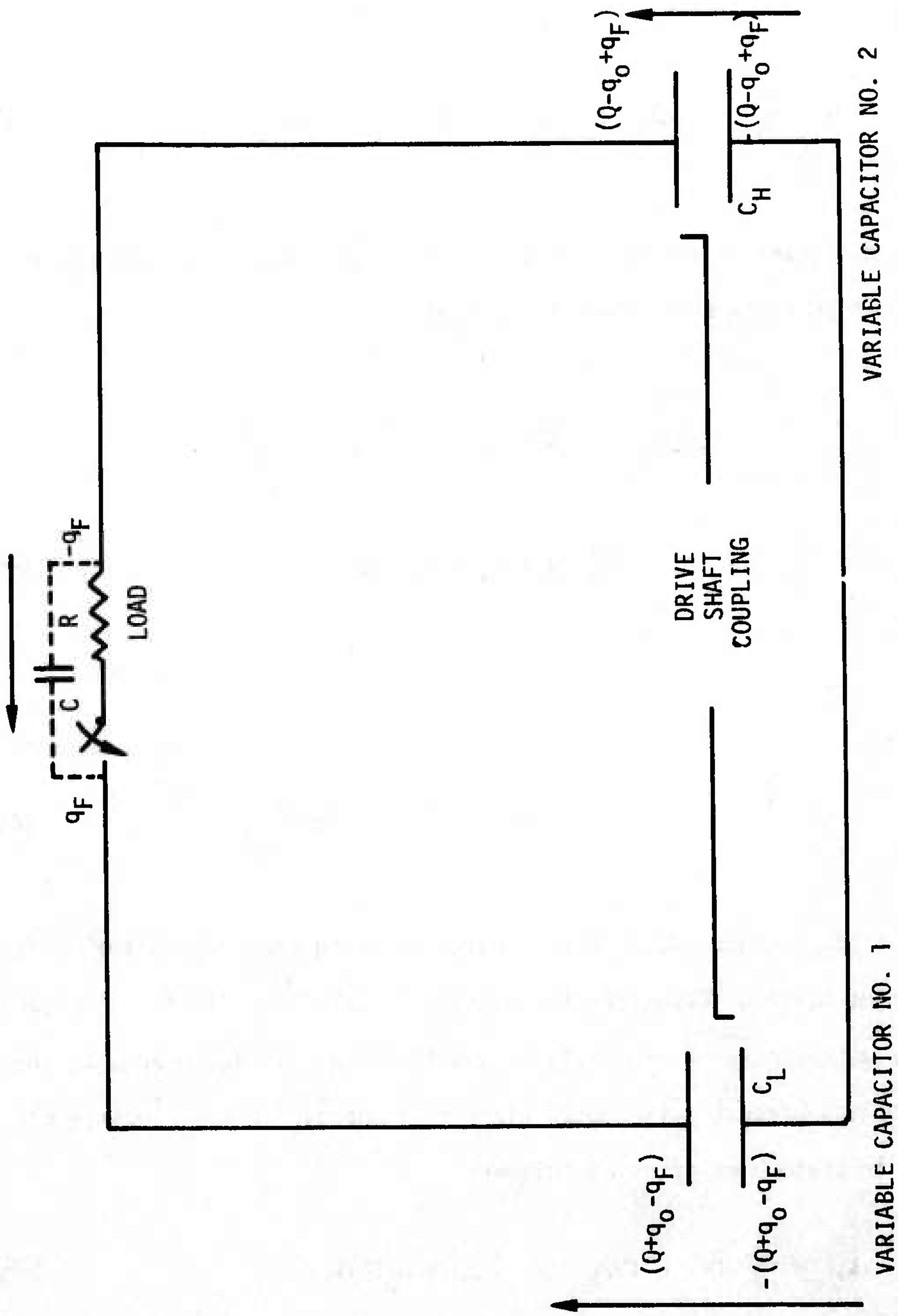

VARIABLE CAPACITOR NO. 2
$(Q-q_o+q_F)$
$-(Q-q_o+q_F)$
C_H
DRIVE
SHAFT
COUPLING
LOAD
R
C
q_F
$-q_F$
C_L
$(Q+q_o-q_F)$
$-(Q+q_o-q_F)$
VARIABLE CAPACITOR NO. 1

Figure 4B

has capacitance C_H. The potential rise across Capacitor #1 equals the potential drop across the load plus the potential drop across Capacitor #2:

$$(Q + q_o - q_F)/C_L = q_F/C + (Q - q_o + q_F)/C_H \tag{43}$$

At the instant of firing, the total electrical energy for the electric circuit in State B is given as follows:

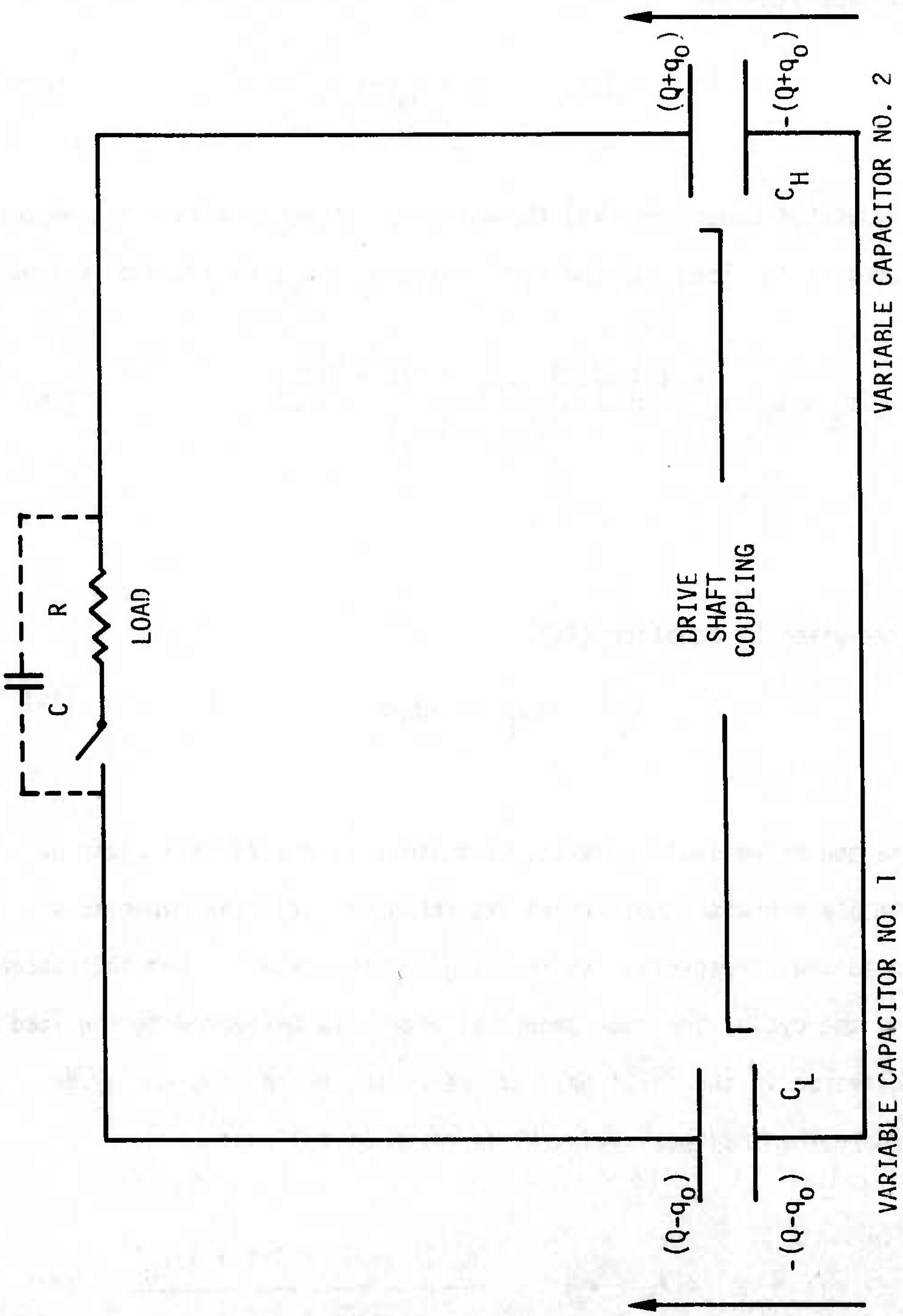
$$W_B = \frac{1}{2}(Q + q_o - q_F)^2/C_L + \frac{1}{2}q_F^2/C + \frac{1}{2}(Q - q_o + q_F)^2/C_H \tag{44}$$

Also,

$$V_F = E_F d = q_F/C \tag{45}$$

<u>State C</u>(Figure 4C): After charge rearrangement, Capacitor #2 is in the same state as Capacitor #1 in State A; Capacitor #1 is in the same state as Capacitor #2 in State A; and the load R is again open to the electrical circuit. The total electrical energy for the electric circuit in State C is given as follows:

$$W_C = \frac{1}{2}(Q - q_o)^2/C_L + \frac{1}{2}(Q + q_o)^2/C_H \tag{46}$$



(Q+q₀)
-(Q+q₀)
C_H
VARIABLE CAPACITOR NO. 2
C
R
LOAD
DRIVE
SHAFT
COUPLING
C_L
(Q-q₀)
-(Q-q₀)
VARIABLE CAPACITOR NO. 1

Figure 4C

The potential rise across Capacitor #1 is equal to the potential drop across Capacitor #2:

$$(Q - q_o)/C_L = (Q + q_o)/C_H \tag{47}$$

By use of Equations (43) through (47), it is seen that the energy delivered to the load for the half cycle, $W_B - W_C$, is given as follows:

$$W_B - W_C = \frac{\left(\frac{1}{2}\, q_F^2/C\right)\,(1/C_L + 1/C + 1/C_H)}{(1/C_L + 1/C_H)} \tag{48}$$

With, as given by Equation (45),

$$q_F = CV_F = CE_F d \tag{49}$$

As the drive shaft rotates, Capacitors #1 and #2 will again go through State B with their roles interchanged until the capacitors return to their respective states as given in State A. For this second half of the cycle, the same amount of energy is delivered to the load as was delivered in the first half of the cycle; hence, the energy delivered to the load per cycle, W, is given as follows:

$$W = 2(W_B - W_C) = \frac{(q_F^2/C)\,(1/C_L + 1/C + 1/C_H)}{(1/C_L + 1/C_H)} \tag{50}$$

The limit on energy transfer may be expressed in terms of V_F or E_F as they are related to q_F as given by Equation (49).

In addition, provision could be made for controlled switching (not self-firing); such as a controlled switch in series with the load R, both in parallel with the load area capacitor C, and a controlled switch in series with the load area and variable capacitors. This could allow for charging of capacitor C, switchout of the variable capacitors from the load area, and switchon of the charged capacitor C (by the controlled switch in series with R) for its fast, pulsed energy input into the load R.

SECTION V

PULSED ENERGY INPUT, GENERATORS INDIRECTLY CONNECTED TO LOAD THROUGH DIELECTRIC MATERIAL, SELF-SWITCHING LOAD

State A(Figure 5A): Capacitor #1 has capacitance C_H and a charge $(Q + q_o)$; Capacitor #2 has capacitance C_L and a charge $(Q - q_o)$; the potential rise across Capacitor #2 is equal to the potential drop across each dielectric (of capacitance c_d) and Capacitor #1:

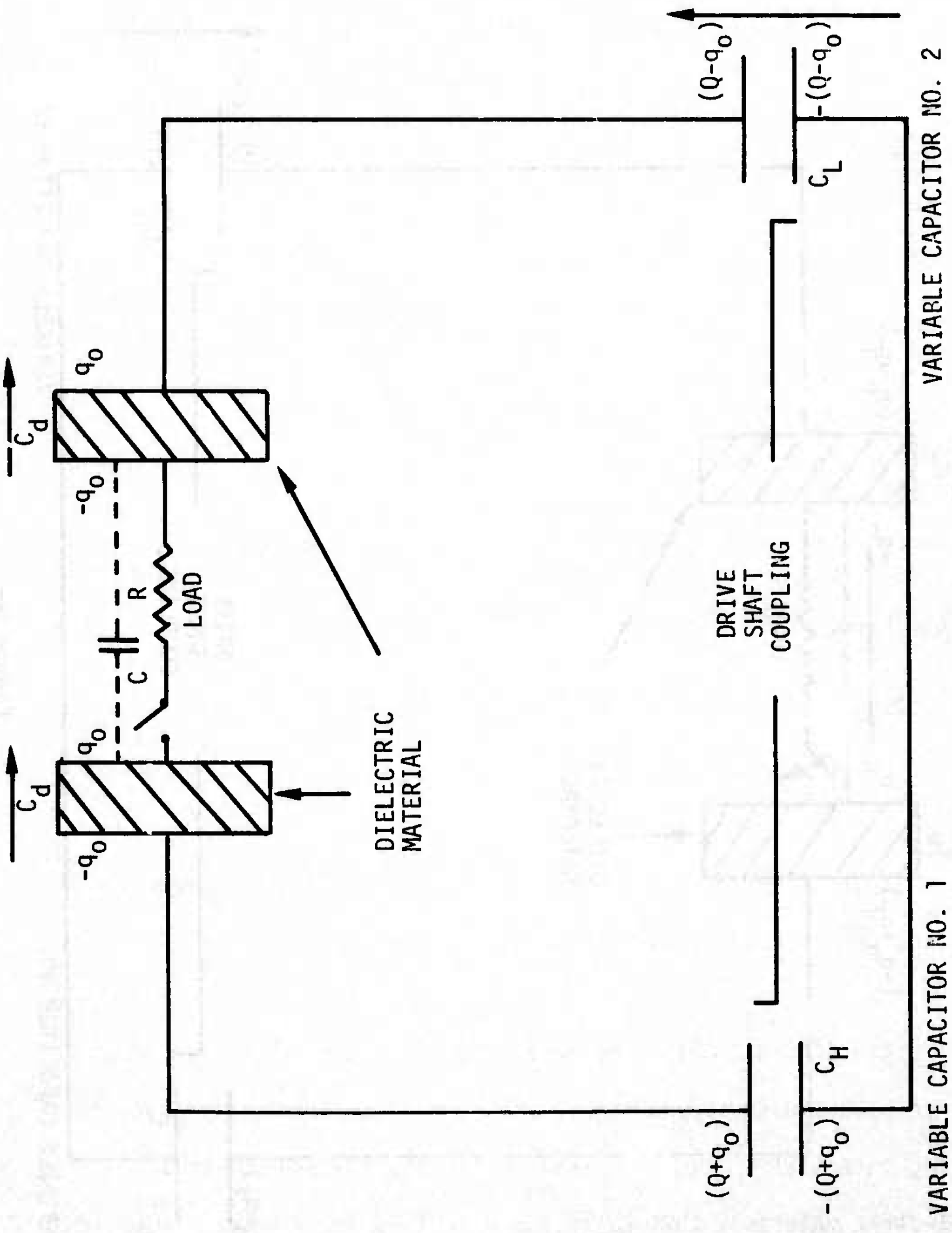
$$(Q - q_o)/C_L = 2q_o/c_d + (Q + q_o)/C_H \tag{51}$$

The load R is open to the electric circuit and the capacitance of the area between the dielectric material has the value C. The total electrical energy of the electric circuit in State A is given as follows:

$$W_A = \frac{1}{2}(Q + q_o)^2/C_H + q_o^2/c_d + \frac{1}{2}(Q - q_o)^2/C_L \tag{52}$$

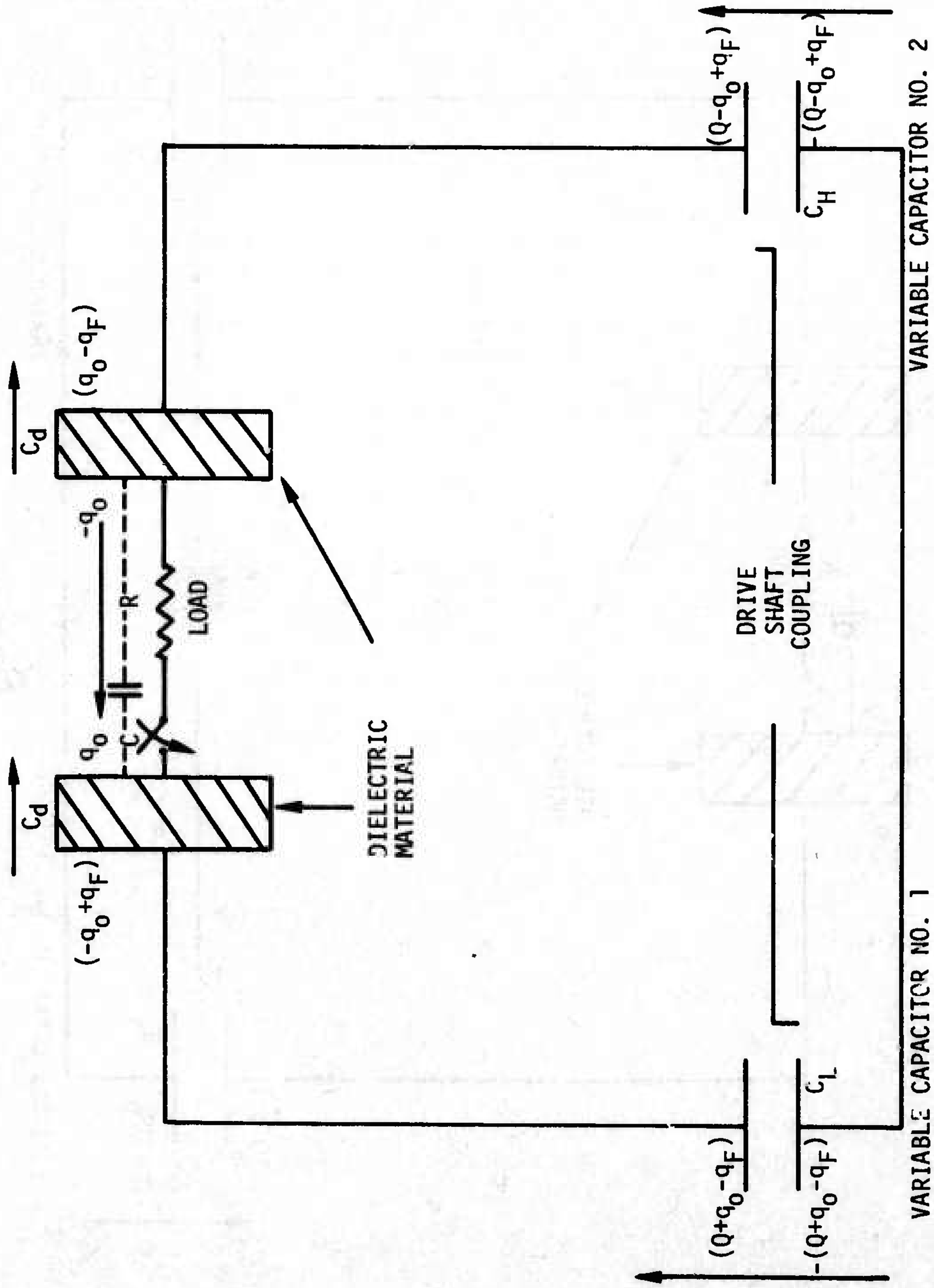
The drive shaft rotates, the capacitance of Capacitors #1 and #2 changes, and the charge redistributes itself.

State B(Figure 5B): The instant of firing has been reached. A charge q_F has distributed itself on the dielectric material such that firing potential V_F has been achieved across the area between the dielectric material; this V_F is equivalent to the product of the critical (firing) field E_F and the distance between the dielectric material capacitors, d. Capacitor #1 now has capacitance C_L and Capacitor #2 has



C_d
$-q_o$
q_o
C_d
$-q_o$
q_o
C
R
LOAD
DIELECTRIC
MATERIAL
DRIVE
SHAFT
COUPLING
$(Q+q_o)$
$-(Q+q_o)$
C_H
VARIABLE CAPACITOR NO. 1
$(Q-q_o)$
$-(Q-q_o)$
C_L
VARIABLE CAPACITOR NO. 2

Figure 5A



C_d
$(-q_o+q_F)$
q_o
C
R
$-q_o$
LOAD
C_d
(q_o-q_F)
DIELECTRIC MATERIAL
DRIVE SHAFT COUPLING
$(Q+q_o-q_F)$
$-(Q+q_o-q_F)$
C_L
VARIABLE CAPACITOR NO. 1
$(Q-q_o+q_F)$
$-(Q-q_o+q_F)$
C_H
VARIABLE CAPACITOR NO. 2

Figure 5B

capacitance C_H. It is assumed that the capacitance of the area between the dielectric material, C, is much less than that of the capacitance of the dielectric material itself, c_d. The potential rise across Capacitor #1 plus the potential rise across the dielectric capacitors equal the potential drop across the area between the dielectric material plus the potential drop across Capacitor #2:

$$(Q + q_o - q_F)/C_L + 2(q_o - q_F)/c_d = q_F/C + (Q - q_o + q_F)/C_H \tag{53}$$

At the instant of firing, the total electrical energy for the electric circuit in State B is given as follows:

$$W_B = \frac{1}{2}(Q + q_o - q_F)^2/C_L + (q_o - q_F)^2/c_d + \frac{1}{2}q_F^2/C + \frac{1}{2}(Q - q_o + q_F)^2/C_H \tag{54}$$

Also,

$$V_F = E_F d = q_F/C \tag{55}$$

State C(Figure 5C): After charge rearrangement, Capacitor #2 is in the same state as Capacitor #1 in State A; Capacitor #1 is in the same state as Capacitor #2 in State A; and the load R is again open to the electrical circuit. The total electrical energy for the electric circuit in State C is given as follows:

$$W_C = \frac{1}{2}\left(Q - q_o\right)^2/C_L + q_o^2/c_d + \frac{1}{2}\left(Q + q_o\right)^2/C_H \qquad (56)$$

The potential rise across Capacitor #1 is equal to the potential drops across the dielectric capacitors c_d and the potential drop across Capacitor #2:

$$\left(Q - q_o\right)/C_L = 2q_o/c_d + \left(Q + q_o\right)/C_H \qquad (57)$$

By use of Equations (53) through (57), it is seen that the energy delivered to the load for the half cycle, $W_B - W_C$, is given as follows:

$$W_B - W_C = \frac{\left(\frac{1}{2}\, q_F^2/C\right)\left(1/C_L + 2/c_d + 1/C + 1/C_H\right)}{\left(1/C_L + 2/c_d + 1/C_H\right)} \qquad (58)$$

With, as given by Equation (55),

$$q_F = CV_F = CE_F d \qquad (59)$$

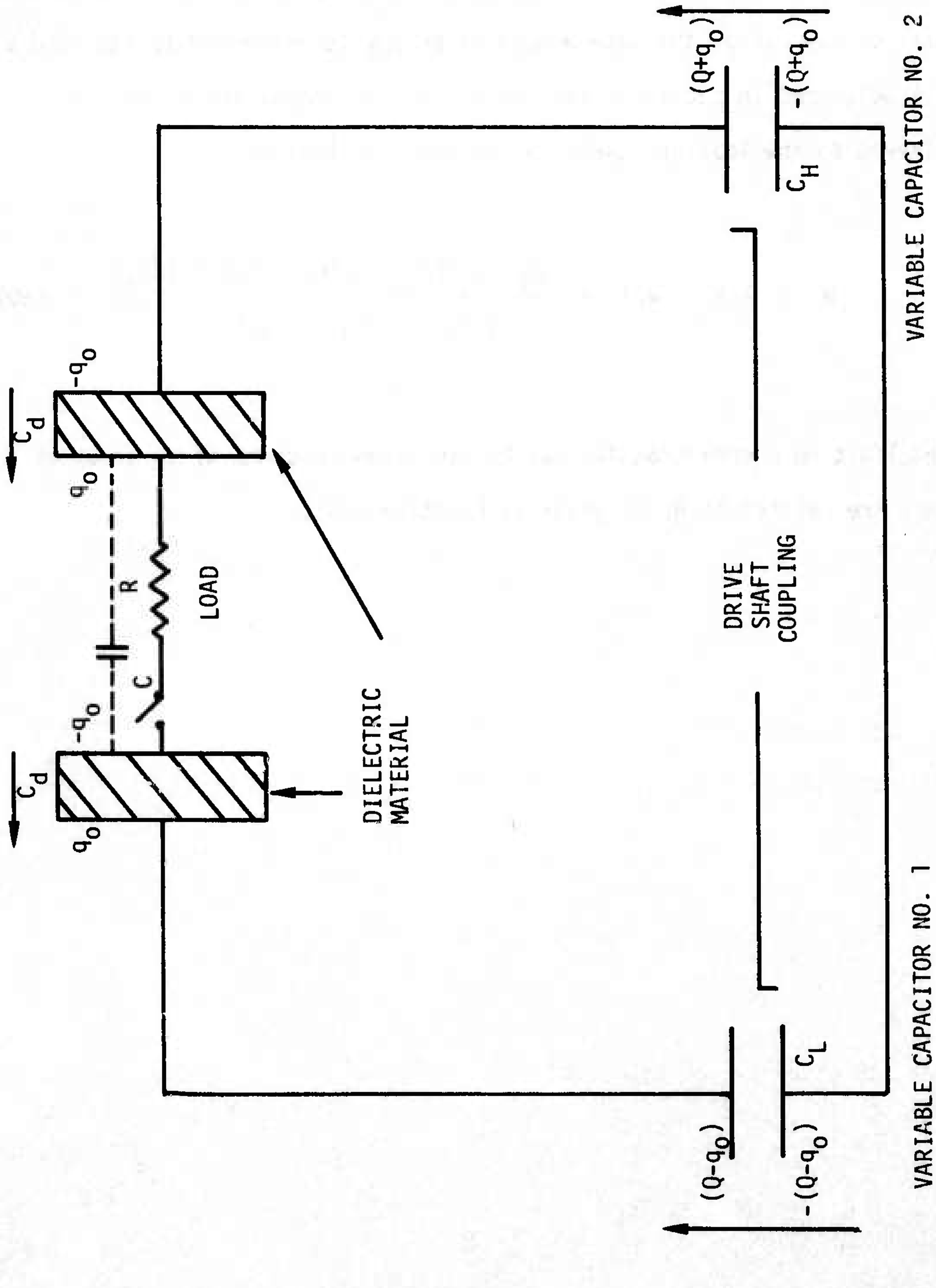

(Q+q_o)
-(Q+q_o)
C_H
VARIABLE CAPACITOR NO. 2
-q_o
C_d
q_o
R
LOAD
C
-q_o
C_d
q_o
DIELECTRIC MATERIAL
DRIVE SHAFT COUPLING
C_L
(Q-q_o)
-(Q-q_o)
VARIABLE CAPACITOR NO. 1

Figure 5C

As the drive shaft rotates, Capacitors #1 and #2 will again go through State B with their roles interchanged until the capacitors return to their respective states as given in State A. For this second half of the cycle, the same amount of energy is delivered to the load as was delivered in the first half of the cycle; hence, the energy delivered to the load per cycle, W, is given as follows:

$$W = 2(W_B - W_C) = \frac{(q_F^2/C)\ (1/C_L + 2/c_d + 1/C + 1/C_H)}{(1/C_L + 2/c_d + 1/C_H)} \qquad (60)$$

The limit on energy transfer may be expressed in terms of V_F or E_F as they are related to q_F as given by Equation (59).

SECTION VI

CONTINUOUS (CW) INPUT, GENERATORS DIRECTLY CONNECTED TO LOAD

Consider the system schematic as given by Figure 6; and, at time $t = 0$, the Variable Capacitors #1 and #2 have the same capacitance, the same charge Q, and hence are at the same potential. Capacitor #2 is out of phase with Capacitor #1 by half a period; the capacitors vary periodically with period T(seconds).

The circuit equation for the transported charge q is as follows, assuming neglible circuit inductance:

$$(Q - q)/C_1 = R\frac{dq}{dt} + (Q + q)/C_2 \tag{61}$$

with $q = 0$, for $t = 0$.

With sinusoidal input to the load, for the following assumed capacitance:

$$C_1 = \frac{1}{\frac{1}{C_H} + \left(\frac{1}{C_L} - \frac{1}{C_H}\right)\left[\frac{1 - \cos\frac{2\pi}{T}\left(t + \frac{T}{4}\right)}{2}\right]} \tag{62}$$

$$C_2 = \frac{1}{\frac{1}{C_H} + \left(\frac{1}{C_L} - \frac{1}{C_H}\right)\left[\frac{1 + \cos\frac{2\pi}{T}\left(t + \frac{T}{4}\right)}{2}\right]} \tag{63}$$

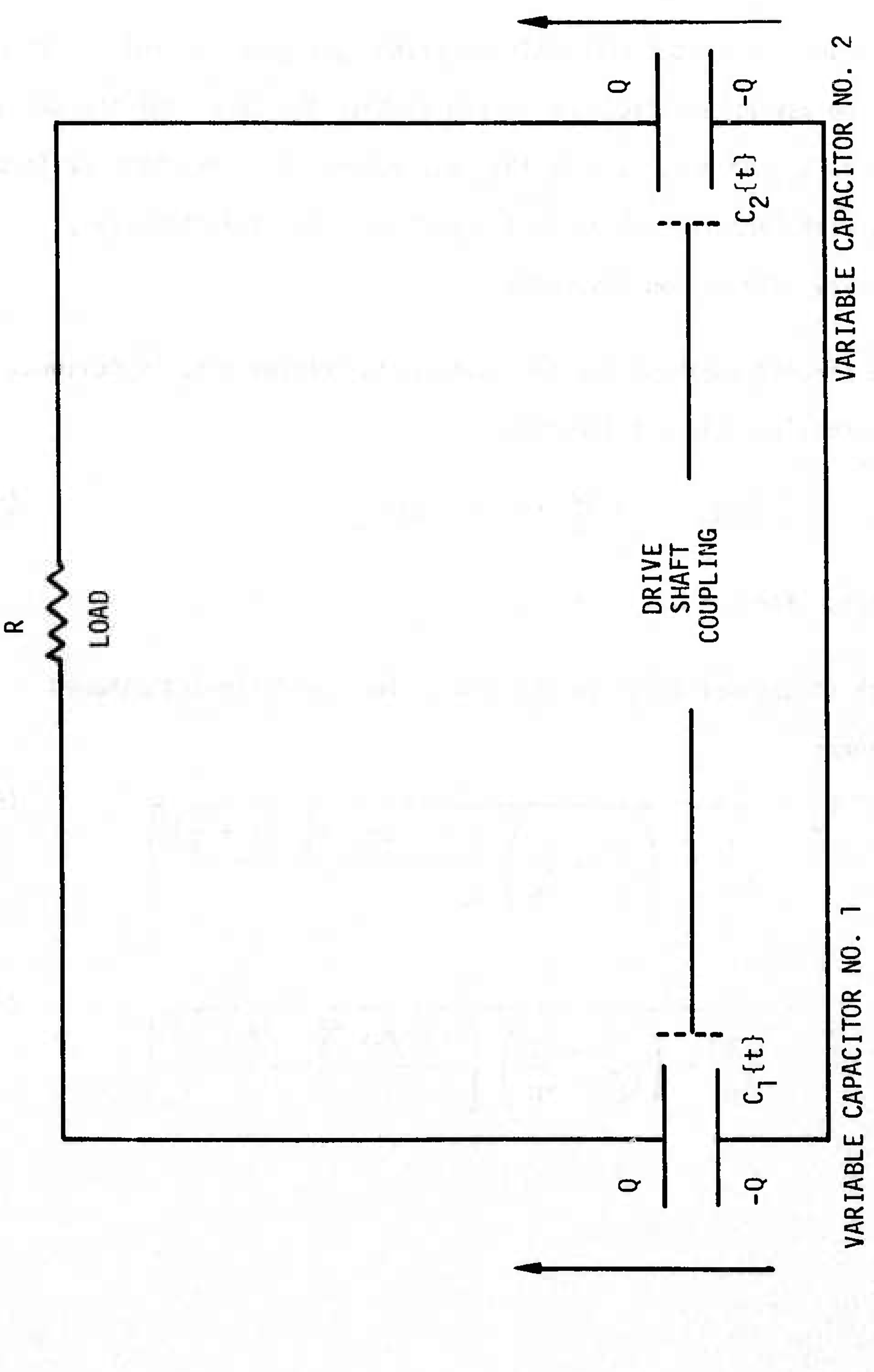

Q
-Q
$C_2\{t\}$
VARIABLE CAPACITOR NO. 2
R
LOAD
DRIVE SHAFT COUPLING
Q
-Q
$C_1\{t\}$
VARIABLE CAPACITOR NO. 1

Figure 6

the solution for q is given as follows:

$$q = \frac{\frac{Q}{R}\left[\frac{1}{C_L} - \frac{1}{C_H}\right]}{\sqrt{\left(\frac{2\pi}{T}\right)^2 + \left[\frac{1}{R}\left(\frac{1}{C_L} + \frac{1}{C_H}\right)\right]^2}} \left[\begin{array}{l} \cos\left[\frac{\pi}{2} - \arctan\left(\left[\frac{2\pi}{T}\right] / \left[\frac{1}{R}\left[\frac{1}{C_L} + \frac{1}{C_H}\right]\right]\right)\right] \exp\left[-\frac{1}{R}\left(\frac{1}{C_L} + \frac{1}{C_H}\right)t\right] \\ -\cos\left[\frac{2\pi}{T}\left(t + \frac{T}{4}\right) - \arctan\left(\left[\frac{2\pi}{T}\right] / \left[\frac{1}{R}\left(\frac{1}{C_L} + \frac{1}{C_H}\right)\right]\right)\right] \end{array}\right] \tag{64}$$

with average power, P (watts), given, for the electrical circuit time constant, $1/\left[\frac{1}{R}\left(\frac{1}{C_L} + \frac{1}{C_H}\right)\right]$, much less than T, and after transient decay, as follows:

$$P = \frac{1}{T} \int_t^{t+T} R\left(\frac{dq}{dt}\right)^2 dt = \frac{2\pi^2 R Q^2}{T^2} \frac{\left(C_H - C_L\right)^2}{\left[C_H + C_L\right]^2} \tag{65}$$

and Q limited by the breakdown potential V_{CB} of the capacitors as follows:

$$\left[\frac{(Q - q)}{C_1}\right]_{\text{Maximum}} = \frac{Q(C_H + C_L)}{2C_H C_L} = V_{CB} \tag{66}$$

By use of Equations (65) and (66), the limit on P, P_{CB}, is:

$$P_{CB} = \frac{8\pi^2 C_H C_L (C_H - C_L)^2 V_{CB}^2}{T^2 (C_H + C_L)^3 \frac{1}{R}\left[\frac{1}{C_L} + \frac{1}{C_H}\right]} \tag{67}$$

The range of P is then given as follows:

$$0 \leq P < P_{CB} \tag{68}$$

SECTION VII

CONTINUOUS (CW) INPUT, GENERATORS INDIRECTLY CONNECTED TO LOAD THROUGH DIELECTRIC MATERIAL

Consider the system schematic as given by Figure 7; at time $t = 0$, the Variable Capacitors #1 and #2 have the same capacitance, the same charge Q, and hence are at the same potential. The capacitors vary periodically with period T (seconds), and Capacitor #2 is out of phase with Capacitor #1 by half a period.

The circuit equation for the transported charge q is as follows, assuming negligible circuit inductance:

$$(Q - q)/C_1 = R\frac{dq}{dt} + 2q/c_d + (Q + q)/C_2 \qquad (69)$$

with $q = 0$, for $t = 0$.

With sinusoidal input to the load, for the following assumed capacitance:

$$C_1 = \frac{1}{\frac{1}{C_H} + \left(\frac{1}{C_L} - \frac{1}{C_H}\right)\left[\frac{1 - \cos\frac{2\pi}{T}\left(t + \frac{T}{4}\right)}{2}\right]} \qquad (70)$$

$$C_2 = \frac{1}{\frac{1}{C_H} + \left(\frac{1}{C_L} - \frac{1}{C_H}\right)\left[\frac{1 + \cos\frac{2\pi}{T}\left(t + \frac{T}{4}\right)}{2}\right]} \qquad (71)$$

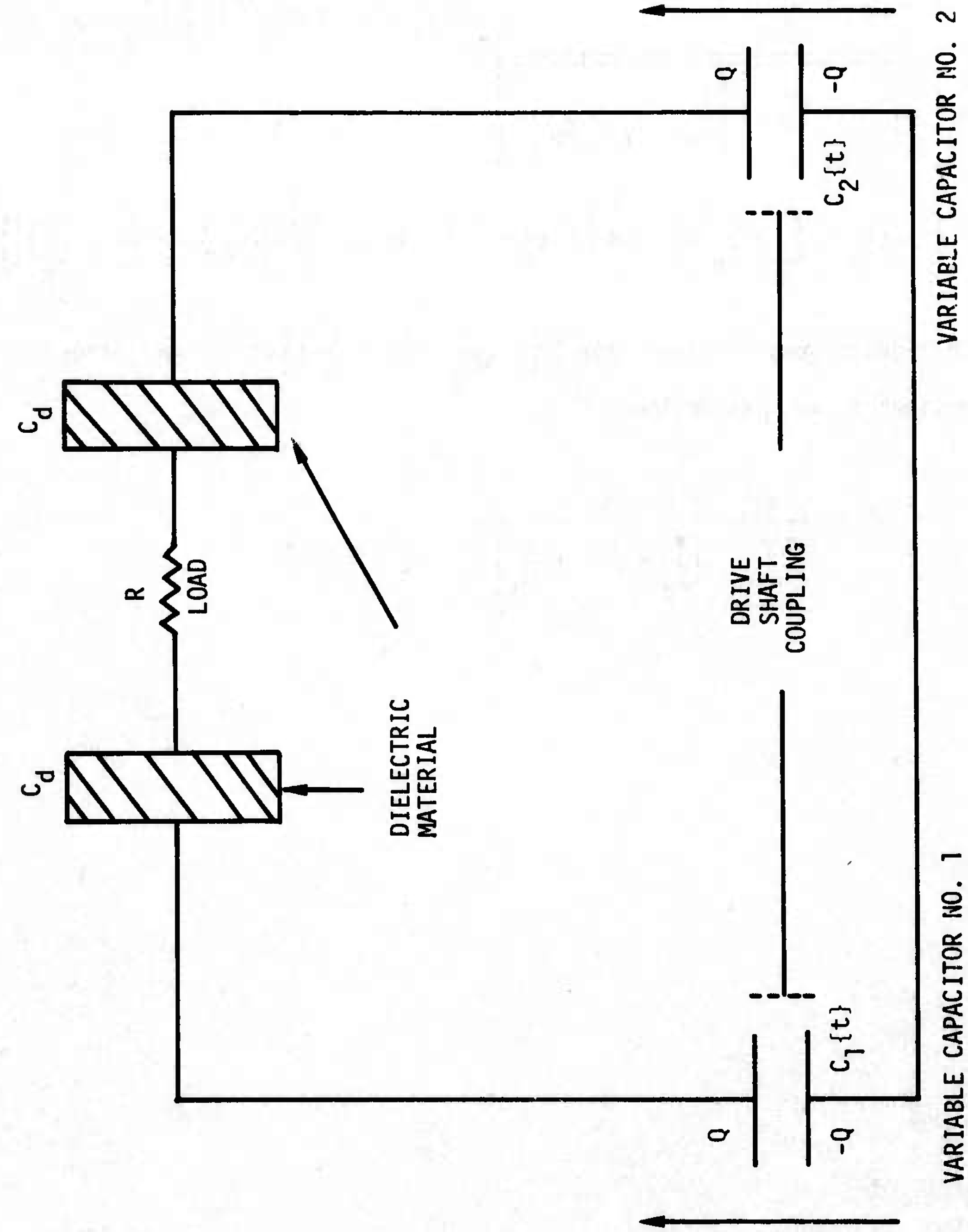

VARIABLE CAPACITOR NO. 1
VARIABLE CAPACITOR NO. 2
Q
-Q
$C_1\{t\}$
$C_2\{t\}$
C_d
R
LOAD
DIELECTRIC
MATERIAL
DRIVE
SHAFT
COUPLING

Figure 7

the solution for q is given as follows:

$$q = \frac{\frac{Q}{R}\left[\frac{1}{C_L} - \frac{1}{C_H}\right]}{\sqrt{\left(\frac{2\pi}{T}\right)^2 + \left(\frac{1}{R}\right)^2\left[\frac{2}{C_d} + \frac{1}{C_L} + \frac{1}{C_H}\right]^2}}\left[\cos\left[\frac{\pi}{2} - \arctan\left(\left[\frac{2\pi}{T}\right]\Big/\left[\frac{1}{R}\left(\frac{2}{C_d} + \frac{1}{C_L} + \frac{1}{C_H}\right]\right)\right]\right. \times$$

$$\left. \exp\left[-\frac{1}{R}\left(\frac{2}{C_d} + \frac{1}{C_L} + \frac{1}{C_H}\right)t\right] - \cos\left[\frac{2\pi}{T}\left(t + \frac{T}{4}\right) - \arctan\left(\left[\frac{2\pi}{T}\right]\Big/\left[\frac{1}{R}\left(\frac{2}{C_d} + \frac{1}{C_L} + \frac{1}{C_H}\right)\right]\right)\right]\right] \quad (72)$$

with average power P given, for $1/\left[\frac{1}{R}\left(\frac{2}{C_d} + \frac{1}{C_L} + \frac{1}{C_H}\right)\right] << T$, and after transient decay, as follows:

$$P = \frac{2\pi^2 RQ^2}{T^2} \frac{\left[\frac{1}{C_L} - \frac{1}{C_H}\right]^2}{\left[\frac{2}{C_d} + \frac{1}{C_L} + \frac{1}{C_H}\right]^2} \quad (73)$$

SECTION VIII

CAPABILITY

Variable capacitance electrostatic generators (Reference 1) are rugged, efficient (capable of greater than 99% efficiency), can have high rotational speed (capable of at least 1000's of RPM), and can be of high power (capable of 1000's of kilowatts) for practical dimensions. In addition to being essentially free from magnetic losses, the generators, if vacuum insulated, have little resistive heating loss and no windage loss because of the nature of the vacuum insulation. Also, the generators possess much lower weight-to-power ratios than conventional electromagnetic energy conversion equipment.

High breakdown potentials of available insulating materials (References 3-7) for the electrostatic generators (or, more generally, convertors) indicate that high values for voltage, current, and power could be obtained. The insulator (dielectric) between the moving capacitor plates could be, for example, vacuum or fluid, such as gaseous sulfur hexafluoride, (Reference 8).

The energy presented to the load is converted directly in the variable capacitors themselves, with essentially no other intervening electrical apparatus required; in conversion of mechanical to electrical energy, the only resistance in the electrical circuit could be that of the load itself, which would allow for relatively fast power input to the load, especially for pulsed operation.

The contained (or "trapped") charge of the variable capacitors provides for self-excitation of the generators (or, more generally, convertors).

SECTION IX

EXTENSION

Direct current to the load could be provided, as indicated in the schematic given in Figure 8, by rectification of the alternating output of the electrostatic generators, and by smoothing, as indicated schematically by inductance L_S and capacitance C_S, before input to the load.

Provision could also be made, such as by use of a transformer as indicated schematically in Figure 9, for isolation and matching of the load to the variable capacitance electrostatic generator system.

As opposed to only pulsed 'r only CW operation, mixed operation of the system could be considered, with different modes of operation occuring within the cycle.

As opposed to rotational variable capacitance energy conversion, a physical arrange is shown in Figure 10A (with side view, cross-section in Figure 10B), for example, of translational variable capacitance electrostatic energy conversion.

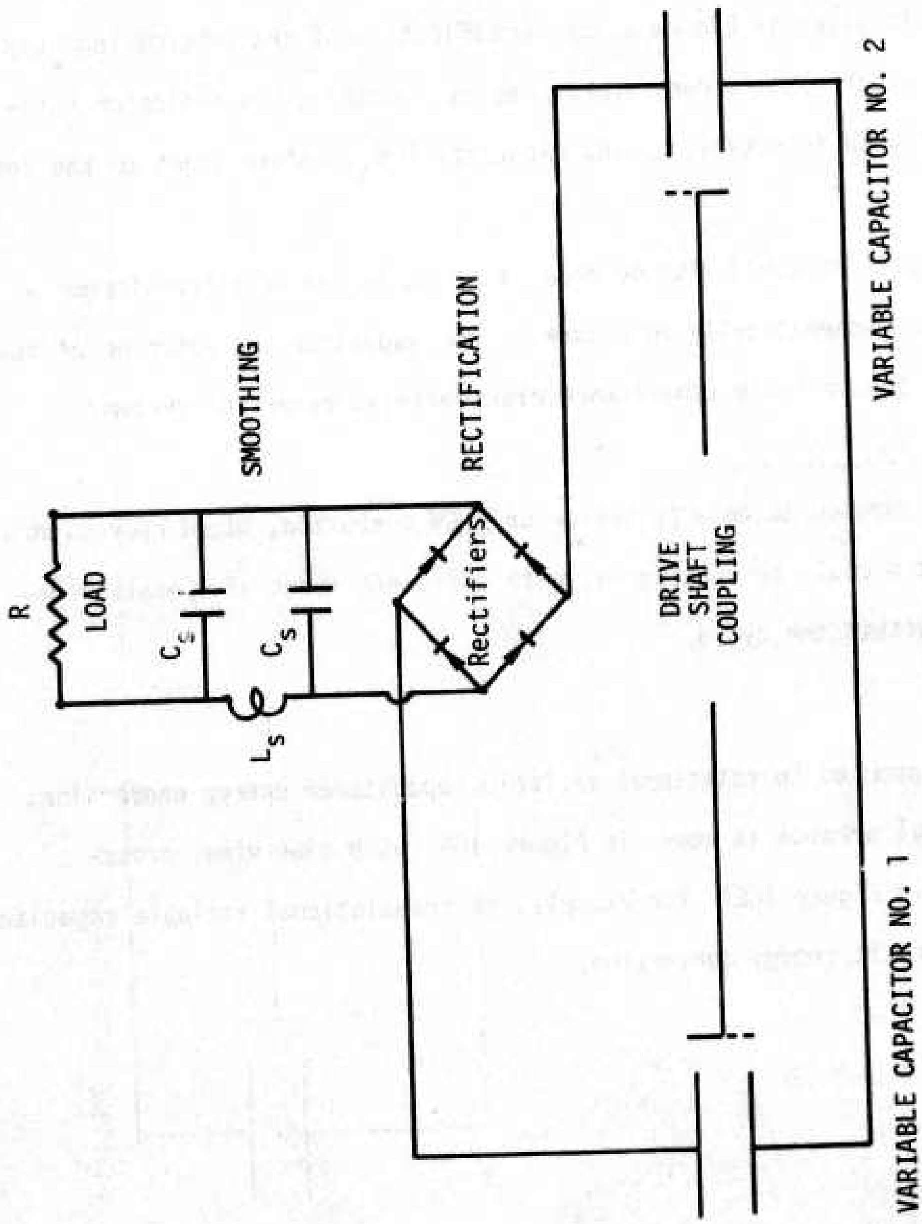

SMOOTHING
RECTIFICATION
R
LOAD
C_S
C_S
L_S
Rectifiers
DRIVE
SHAFT
COUPLING
VARIABLE CAPACITOR NO. 2
VARIABLE CAPACITOR NO. 1

Figure 8

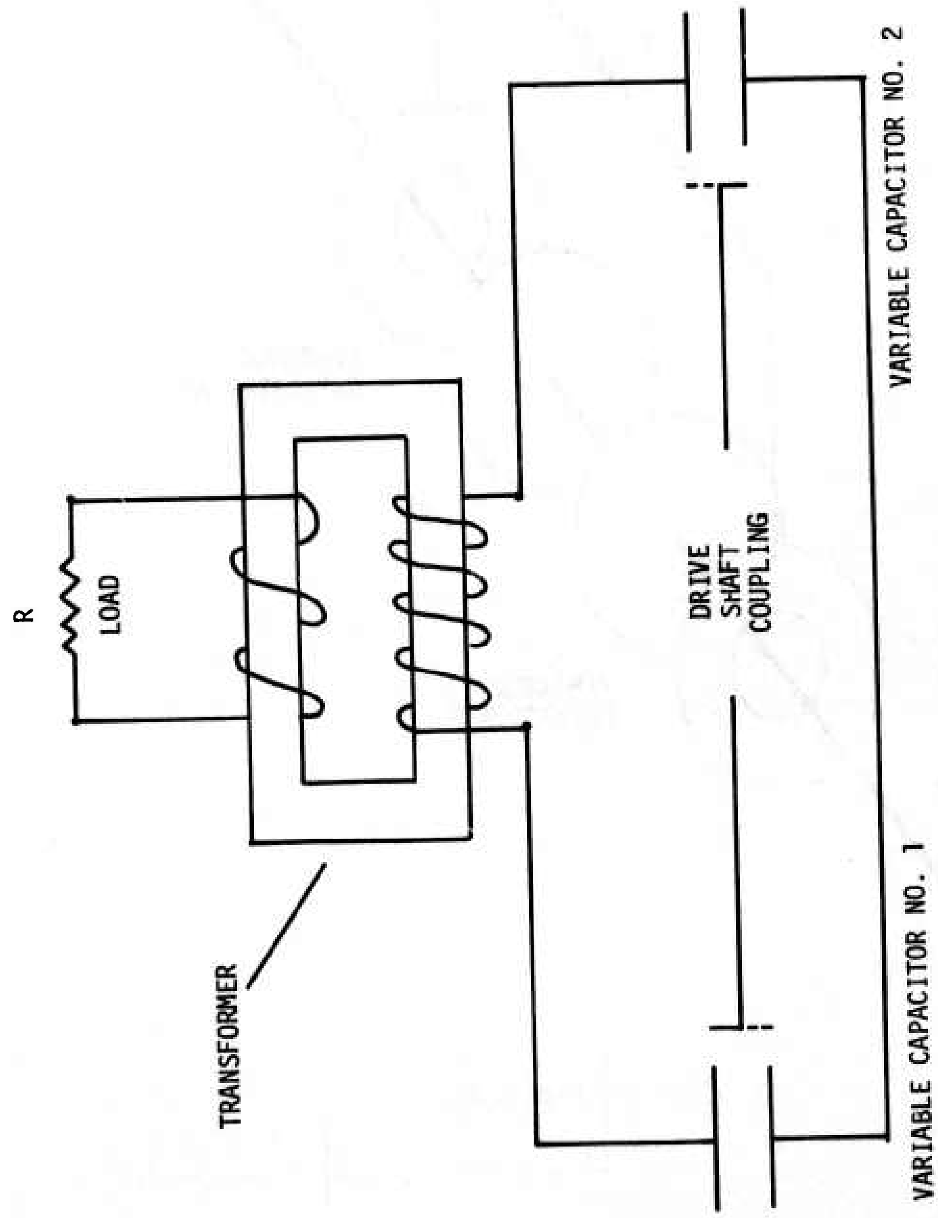

R
LOAD
TRANSFORMER
DRIVE
SHAFT
COUPLING
VARIABLE CAPACITOR NO. 2
VARIABLE CAPACITOR NO. 1

Figure 9

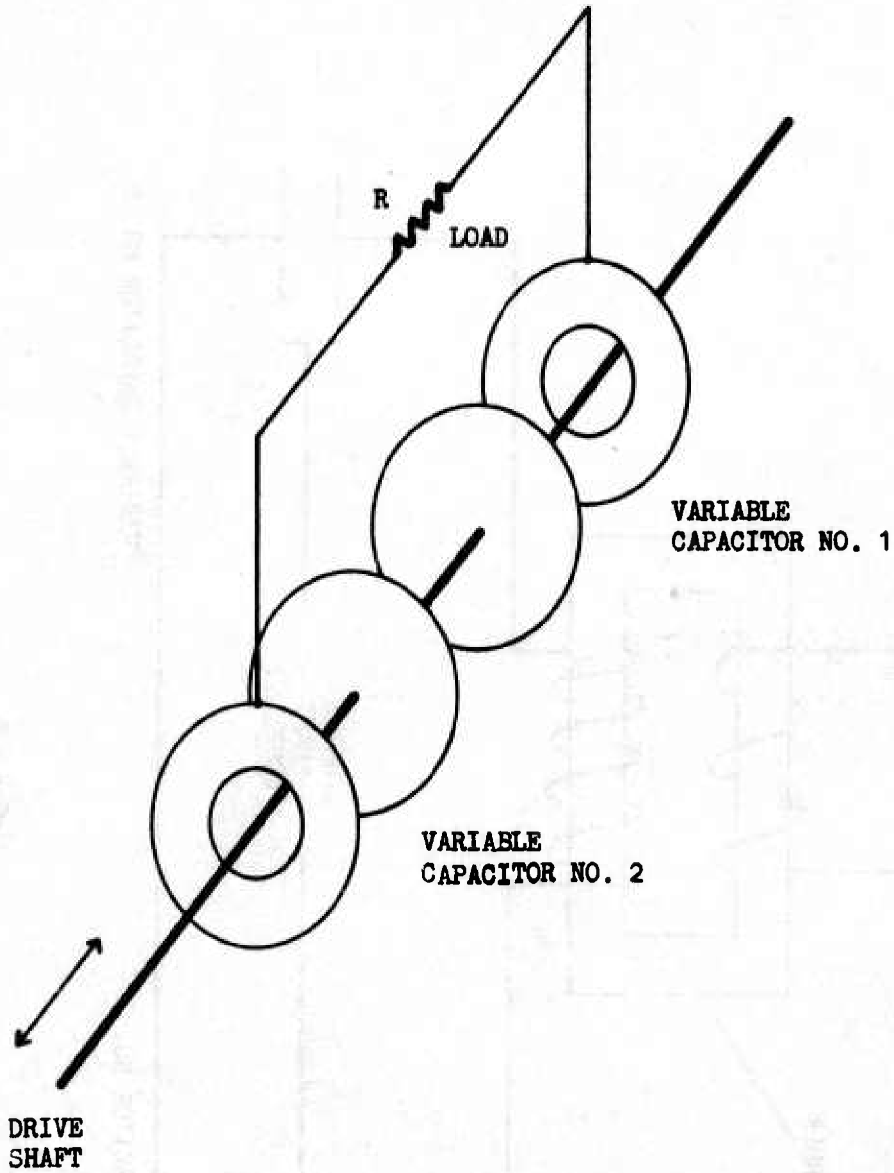

R
LOAD
VARIABLE
CAPACITOR NO. 1
VARIABLE
CAPACITOR NO. 2
DRIVE
SHAFT

Figure 10A

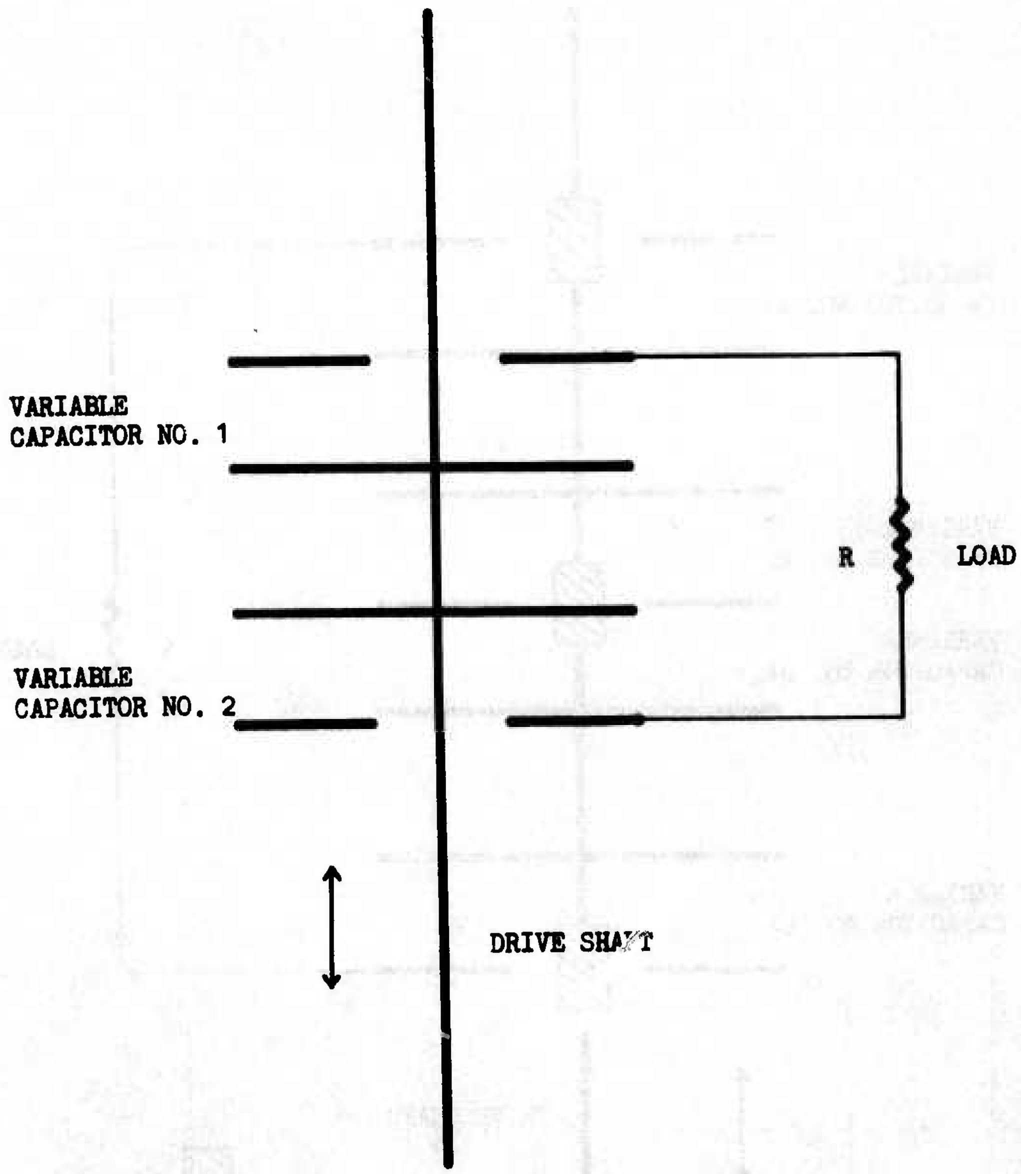

VARIABLE
CAPACITOR NO. 1
R
LOAD
VARIABLE
CAPACITOR NO. 2
DRIVE SHAFT

Figure 10B

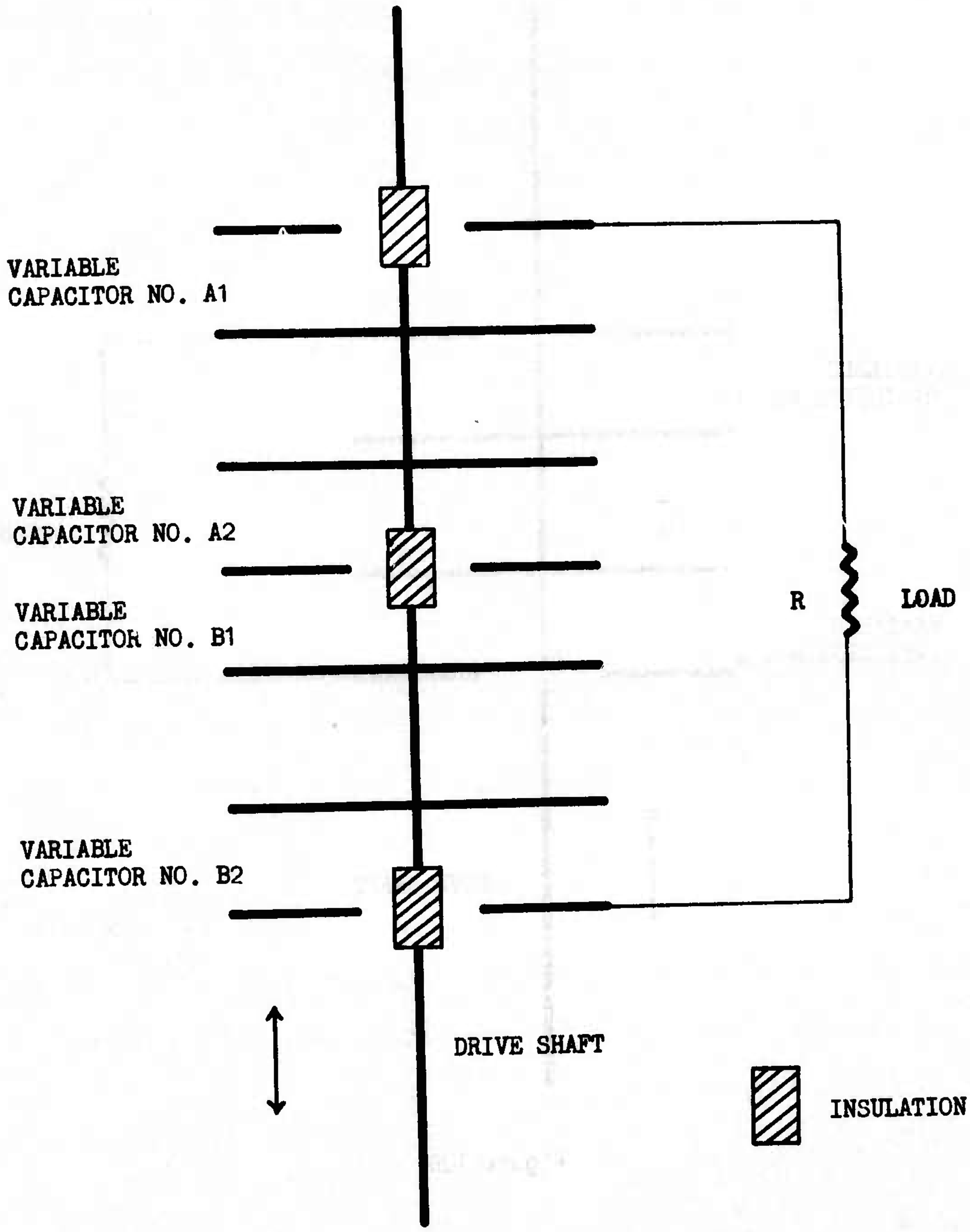

VARIABLE
CAPACITOR NO. A1
VARIABLE
CAPACITOR NO. A2
VARIABLE
CAPACITOR NO. B1
VARIABLE
CAPACITOR NO. B2
R
LOAD
DRIVE SHAFT
INSULATION

Figure 11

As contained implicitly in the definition of Variable Capacitance Electrostatic Energy Conversion System, a multiplicity of variable capacitors could be employed in system application. For example, a number of generator pairs could be placed in opposition across the load (that is, several conversion systems could be placed across the load). Also use of a multiplicity of conversion systems would allow for multi-phased energy conversion. As another example, a system could consist of a number of lesser systems in series, as shown schematically in Figure 11, in order to increase the generator potential capability and thus increase the potential across the load.

Although the conversion system as presented essentially involves the use of contained charge, this charge could be varied in system operation, for example, in order to provide required potential values across the load; that is, the conversion system could be charged or discharged in operation as load conditions, through feedback, dictated.

The specific comments, as presented above, should not be construed as limiting the concrete embodiment or the range of application of the conversion system, but should be considered as indicating a few of the possibilities for the system.

SECTION X

CONVERSION OF ELECTRICAL TO MECHANICAL ENERGY

The electrostatic generators for the Energy Conversion System should not be considered solely as generators, but should be considered generally as converters. As indicated schematically by Figure 12, with a source of electrical power in to the generators (or more generally, converters), electrical energy would be converted into mechanical energy with output of mechanical shaft power.

In addition, systems could possibly be operated as motor-generator sets, for example, some (generators) inputting into others (motors).

For the Variable Capacitance Electrostatic Energy Conversion System, electrical potential is positionally generated, as opposed to being motionally generated as with conventional electromagnetic generators (involving motion of a conductor in a magnetic field); thus the Energy Conversion System could, for example, lend itself naturally to applications for precise positional control.

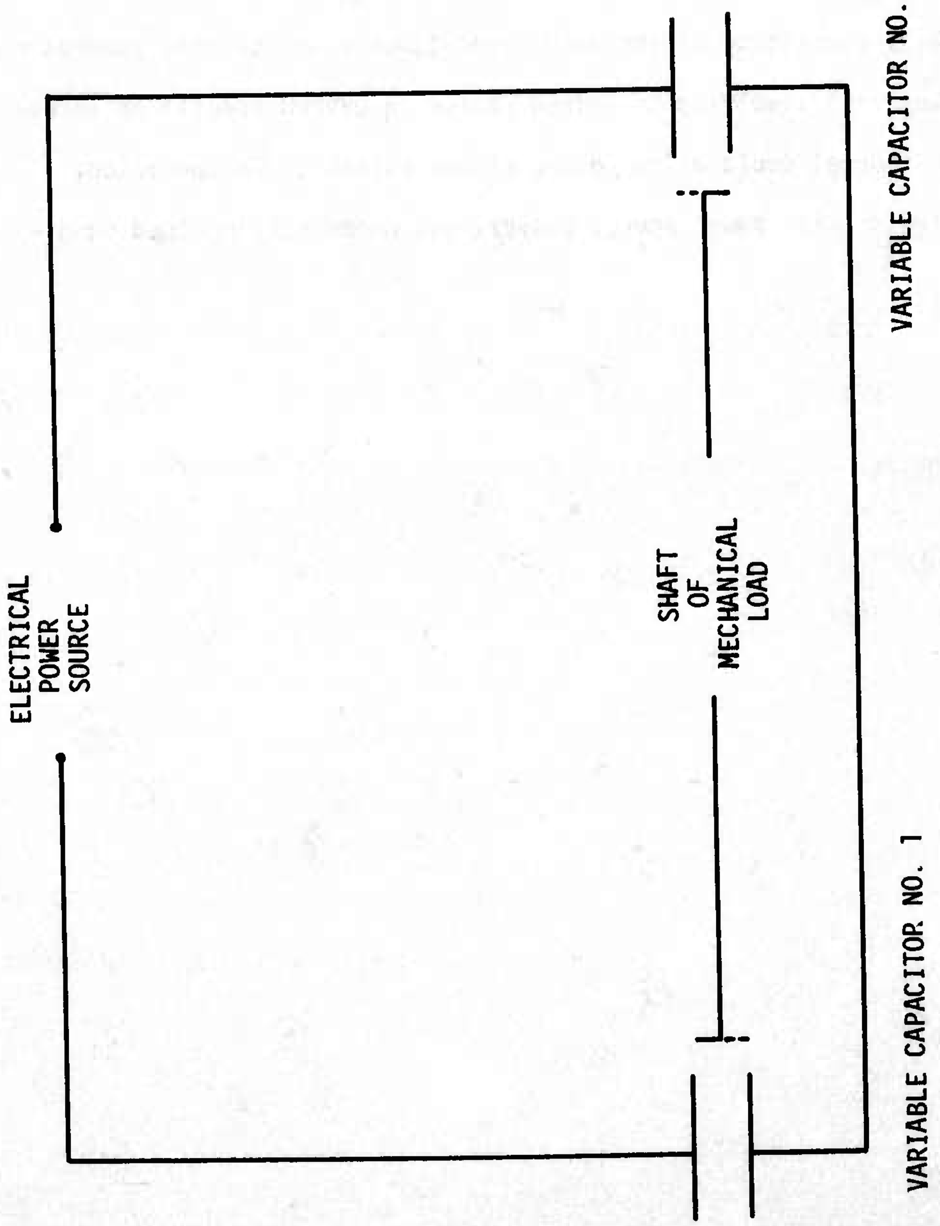

ELECTRICAL
POWER
SOURCE
SHAFT
OF
MECHANICAL
LOAD
VARIABLE CAPACITOR NO. 2
VARIABLE CAPACITOR NO. 1

Figure 12

SECTION XI

CONCLUSION

The Variable Capacitance Electrostatic Energy Conversion System, essentially consisting of variable capacitance electrostatic generators (or converters) involving contained charge in paired opposition across load (or source) could allow, under either pulsed or CW operation, either low or high power energy conversion, under varying load conditions.

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